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BROADBAND COMMUNICATIONS VIA HIGH-ALTITUDE PLATFORMS: A SURVEY

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ABSTRACT

This article is a survey on communication aspects of High Altitude Platforms (HAPs), namely airships or aircraft positioned in the stratosphere between 17 and 22 km. HAPs can be considered as a novel solution for providing telecommunications services. This survey begins with an introduction to HAPs, that is, some historical information and advantages of HAPs compared to terrestrial and satellite networks, followed by information about suitable airships and aircraft, frequency bands allocated to HAPs, possible architectures, and some points on the system structure. We continue with the studies that have been carried out on channel modeling and interference, antennas, transmission and coding techniques. We also refer to access and resource allocation techniques that have been performed so far. Finally, the survey concludes with the types of applications that HAPs are suitable for, in addition to some related projects.

The increasing demand for broadband mobile communications has led to the successful and rapid deployment of both terrestrial and satellite wireless networks. Besides the high data rates, current wireless networks can be inexpensive, support reconfigurability, and provide time- and space-varying coverage at low cost.

In parallel with these two well established methods for providing wireless communication services, in recent years another alternative has attracted the attention of the telecommunications community. It is based on quasi-stationary aerial platforms operating in the stratosphere (Fig. 1), known by different names as High Altitude Platforms[1] (HAPs) or Stratospheric Platforms (SPFs), and located 17–22 km above the Earth's surface. The idea is not new. The Montgolfier brothers invented and demonstrated the hot-air balloons in 1783 and later the German military officer Ferdinand Zeppelin developed the rigid dirigible, lighter-than-air vehicle, known as the zeppelin. Because of safety problems, subsequent activity was mainly confined to hot-air balloons for recreational purposes, small balloons for meteorological use, and tethered aerostats ("balloons on strings" operating at an altitude of 5000m or more). Only in the the past few years has there been a resurgence in balloons and airships due to technology advancement.

[1] *In ITU the term High Altitude Platform Station (HAPS) is used to describe a station located on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth.*

HAPs have similarities and differences with terrestrial wireless and satellite systems, the most important of which are summarized in Table 1, which is an updated version of a table in [1]. The most important advantages of HAP systems are their easy and incremental deployment, flexibility/reconfigurability, low-cost operation, low propagation delay, high elevation angles, broad coverage, broadcast/multicast capability, broadband capability, ability to move around in emergency situations, etc, but there are also crucial disadvantages, such as the monitoring of the station, the immature airship technology, and the stabilization of the on-board antenna. A very interesting feature is that for the same bandwidth allocation terrestrial systems need a huge number of base stations to provide the needed coverage, while GEO satellites face limitations on the minimum cell size projected on the Earth's surface and LEO satellites suffer from handover problems. Therefore, HAPs seem to be a very good design compromise.

As can be seen in Table 1, HAPs represent an economically attractive way for the provision of communications. The cost for the development of satellite systems is much greater, and it may be economically more efficient to cover a large area with many HAPs rather than with many terrestrial base stations or with a satellite system. In addition, due to their long development period, satellite systems always run the risk of becoming obsolete by the time they are in orbit. HAPs also enjoy more favorable path-loss characteristics compared with both terrestrial and satellite systems, while they can frequently take off and land for maintenance and upgrading. Actually, today it is very interesting and challenging to examine and

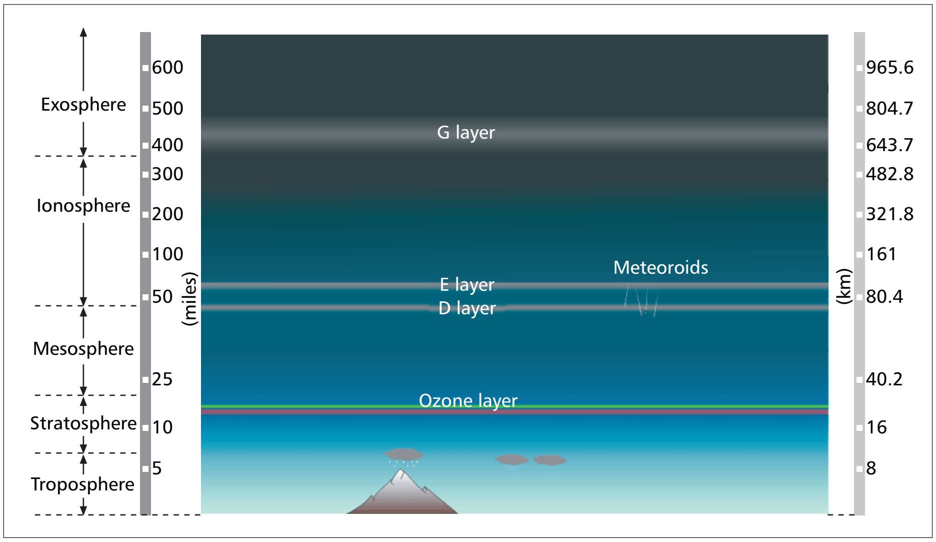


Figure 1. *The atmosphere layers.*

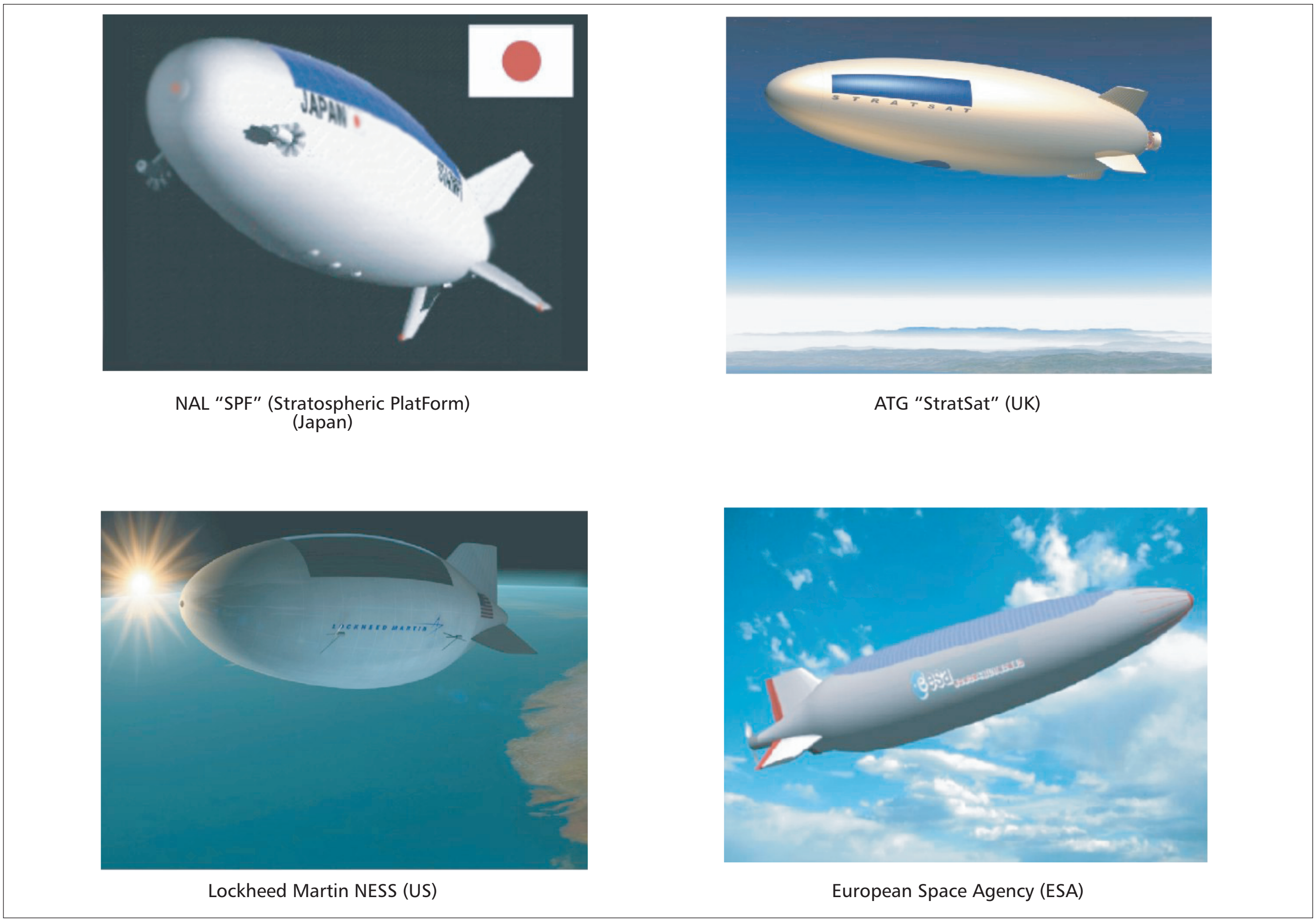


Figure 2. *Solar-powered unmanned airships.*

evaluate a mixed infrastructure comprising HAPs, terrestrial, and satellite systems which could lead to a powerful integrated network infrastructure by making up for the weaknesses of each other [2].

Moreover, the growing exigencies for mobility and ubiquitous access to multimedia services call for the development of new-generation, wireless telecommunications systems. In this respect, 4G networks are expected to fulfill the vision for optimal connectivity anywhere, anytime, providing higher bit rates at low cost, and toward this end, HAPs can play an important role in the evolution of systems beyond 3G. Among the wide spectrum of services that 4G networks are called to support, multicast services represent one of the most interesting categories. However, if Multimedia Broadcast and Multicast Services (MBMS) were to be provided by the terrestrial segment, they would lead to high traffic load. Satellite systems can be

Issue	Terrestrial wireless	Satellite	High Altitude Platform
Availability and cost of mobile terminals	Huge cellular/PCS market drives high volumes resulting in small, low-cost, low-power units	Specialized, more stringent requirements lead to expensive bulky terminals with short battery life	Terrestrial terminals applicable
Propagation delay	Low	Causes noticeable impairment in voice communications in GEO (and MEO to some extent)	Low
Health concerns with radio emissions from handsets	Low-power handsets minimize concerns	High-power handsets due to large path losses (possibly alleviated by careful antenna design)	Power levels like in terrestrial systems (except for large coverage areas)
Communications technology risk	Mature technology and well-established industry	Considerably new technology for LEOs and MEOs; GEOs still lag behind cellular/PCS in volume, cost and performance	Terrestrial wireless technology, supplemented with spot-beam antennas; if widely deployed, opportunities for specialized equipment (scanning beams to follow traffic)
Deployment timing	Deployment can be staged, substantial initial build-out to provide sufficient coverage for commercial service	Service cannot start before the entire system is deployed	One platform and ground support typically enough for initial commercial service
System growth	Cell-splitting to add capacity, requiring system reengineering: easy equipment upgrade/repair	System capacity increased only by adding satellites; hardware upgrade only with replacement of satellites	Capacity increase through spot-beam resizing, and additional platforms; equipment upgrades relatively easy
System complexity due to motion of components	Only user terminals are mobile	Motion of LEOs and MEOs is a major source of complexity, especially when intersatellite links are used	Motion low to moderate (stability characteristics to be proven)
Operational complexity and cost	Well-understood	High for GEOs, and especially LEOs due to continual launches to replace old or failed satellites	Some proposals require frequent landings of platforms (to refuel or to rest pilots)
Radio channel "quality"	Rayleigh fading limits distance and data rate, path loss up to 50 dB/decade; good signal quality through proper antenna placement	Free-space-like channel with Ricean fading; path loss roughly 20 dB/decade; GEO distance limits spectrum efficiency	Free-space-like channel at distances comparable to terrestrial
Indoor coverage	Substantial coverage achieved	Generally not available (high-power signals in Iridium to trigger ringing only for incoming calls)	Substantial coverage possible
Breadth of geographical coverage	A few kilometres per base station	Large regions in GEO (up to the 34% of the earth surface); global for LEO and MEO	Hundreds of kilometers per platform (up to 200km)
Cell diameter	0.1–1 km	50km in the case of LEOs. More than 400km for GEOs	1–10 km
Shadowing from terrain	Causes gaps in coverage; requires additional equipment	Problem only at low elevation angles	Similar to satellite
Communications and power infra-structure; real estate	Numerous base stations to be sited, powered, and linked by cables or microwaves	Single gateway collects traffic from a large area	Comparable to satellite
Esthetic issues and health concerns with towers and antennas	Many sites required for coverage and capacity; "smart" antennas might make them more visible; continued public debates expected	Earth stations located away from populated areas	Similar to satellite
Public safety concern about flying objects	Not an issue	Occasional concern about space junk falling to Earth	Large craft floating or flying overhead can raise significant objections
Cost	Varies	More then $200 million for a GEO system. Some billion for a LEO system (e.g., $5 billion for Iridium, $9 billion for Teledesic)	Unspecified (probably more than $50 million), but less than the cost required to deploy a terrestrial network with many base stations

Table 1. *Basic characteristics of terrestrial wireless, satellite, and HAP systems.*

AeroVironment /NASA
"HELIOS" (US)
Wingspan: 75m
Payload: 50 - 100kgr

AeroVironment /NASA
"Pathfinder Plus" (US)
Wingspan: 36.9m
Payload: 50kgr

HELINET project Heliplat
(Artist's impression)
(Politechnico di Torino)
Wingspan: 70m
Payload: 100kgr

Figure 3. *Solar-powered unmanned aircraft.*

Angel Technologies HALO (Proteus 9)
Manned aircraft for the delivery of communication services

M-55 stratospheric aircraft
(Geoscan Network)
Piloted aircraft for the delivery of wireless services and remote sensing

Figure 4. *Manned aircraft.*

Global Hawk (US)
Altitude: 65,000 feet
Speed: 454 mph

Predator (US)
Altitude: 25,000 feet
Speed: 135 mph

Figure 5. *Unmanned fueled aircraft.*

employed for the distribution of this kind of service by virtue of their intrinsic capability of broadcasting and multicasting. Even though satellite systems possess many attractive features, some of their advantages are negated by the large propagation delays in the case of MEO and GEO satellites, and the unreliability of the satellite channel and the high complexity in the case of LEO satellite systems. To this end, HAP systems can be employed since they represent a solution preserving most of the advantages of satellites, while avoiding some of their drawbacks.

Although HAPs are conceived as complementary systems to terrestrial and satellite networks, the potential of stand-alone HAP systems was discussed in some studies. It is rather difficult and economically inefficient to cover remote and impervious areas with cellular networks, xDSL, or fiber networks. However, HAPs constitute a real asset to wireless infrastructure operators to provide telecommunication services in these areas.

Except for the case where a HAP can be used to provide many users with access to core networks, two other positions of the HAP in the end-to-end path can be distinguished. A HAP can be employed, in isolation from any core networks, in order to connect private networks, such as corporate LANs, or to provide trunk connections between core networks.

In this survey, some system structure information is given, in addition to the frequency bands allocated to HAPs. Then, several studies in the area of network design, channel modeling, interference, and antennas are summarized. We also refer to studies focused on resource management. Finally, we present the potential applications of HAP networks and related projects. At this point it is worth mentioning that when several studies were focused on a specific topic, these were referenced in the text on a time-line basis, with the first citation representing the most seminal work in the field.

Aerial Vehicles, Key Issues and Spectrum Allocation

Types of Aerial Vehicles

Throughout the history of HAPs we can distinguish three categories of proposed aerial vehicles:

- **Unmanned airships** (essentially balloons, termed "aerostats") with propulsion systems, which are semi-rigid or non-rigid, huge and mainly solar-powered balloons, over 100 m long with a payload of about 800 kg or more (Fig. 2). The aim is that this type of aerial vehicle should be able to stay aloft up to five years or more.

	Airships (unmanned)	Solar-powered unmanned aircraft	Manned aircraft
Size	Length 150 ~ 200 m	Wingspan 35 ~70 m	Length ≈ 30 m
Total weight	≈ 30 ton	≈ 1 ton	≈ 2.5 ton
Power source	Solar cells (+fuel cells)	Solar cells (+fuel cells)	Fossil fuel
Environmentally friendly	✔	✔	✘
Response in emergency situations	✘	✔	✔
Flight duration	Up to five years	Unspecified (≈ 6 months)	4-8 hours
Position keeping (radius)	Within 1 km cube	1-3 km	≈ 4 km
Mission payload	1000 ~ 2000 kg	50 ~ 300 kg	Up to 2000 kg
Power for mission	≈ 10 kW	≈ 3 kW	≈ 40 kW
Example	Japan, Korea, China, ATG, Lockheed Martin, SkyStation etc.	Helios, Pathfinder Plus (AeroVironment), Heliplat (European project)	HALO (Angel Technologies) M-55 (Geoscan Network)

Table 2. *A general comparison among airships, solar-powered unmanned aircraft, and manned aircraft.*

- **Solar-powered unmanned aircraft**, also known as High Altitude Long Endurance Platforms (HALE Platforms), use electric motors and propellers as propulsion, while solar cells mounted on the wings and stabilizers provide power during the day and charge the on-board fuel cells (Fig. 3). Although the average flight duration of such vehicles has not been specified yet, some proposals make claims of continuous flight up to six months or more.
- **Manned aircraft**, which have an average flight duration of several hours due to fuel constraints and human factors (Fig. 4).

Solar-powered unmanned aircraft and manned aircraft are also called High Altitude Aeronautical Platforms (HAAPs).

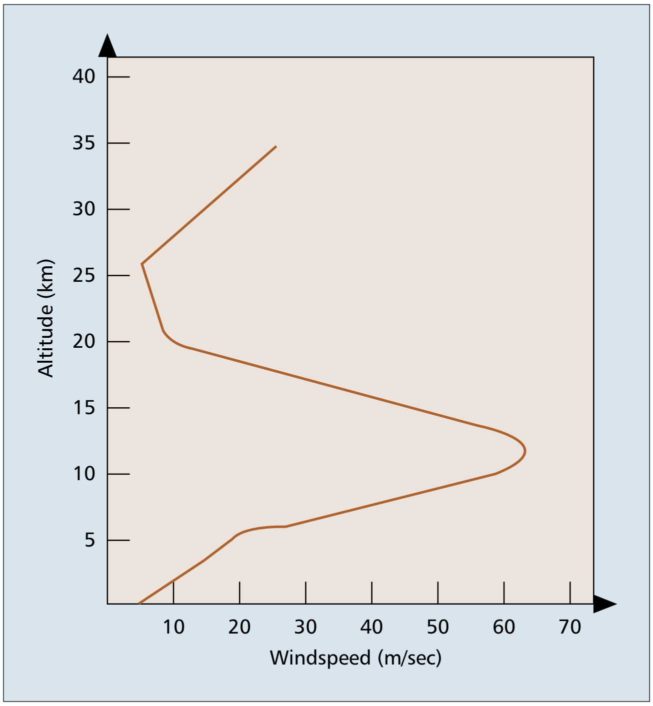


Figure 6. *Wind velocity with respect to the altitude. (This figure appeared in [4].)*

Table 2 (an updated version of the table in [3]) provides a general comparison of the three types of aerial vehicles. Figure 5 presents another type of unmanned aircraft, often referred to as unmanned aerial vehicles (UAVs), which are *small fueled unmanned airplanes*. They are used only for military short-time surveillance (up to 40 hours), and they fly generally at modest altitudes.

HAPs are located at 17–22 km above the Earth's surface because these altitudes are well above the air lanes, the wind conditions in the stratosphere are normally predictable (the average wind velocities are shown in Fig. 6 with season and location variations) and, further, the zone of 17 to 22 km suffers from a relatively mild turbulence. The most preferable altitudes fall from 19 to 22 km, while from 17 to 19 km the velocities are also low. Generally, wind velocities increase over the altitude of 25 km. Besides, as the altitude increases the air density is reduced, making the placement of the vehicle very difficult. For example, at 12 km (the maximum altitude of airplane lanes) the density is about 25 percent compared to that at the sea level, while at 24 km it is only about 3.6 percent.

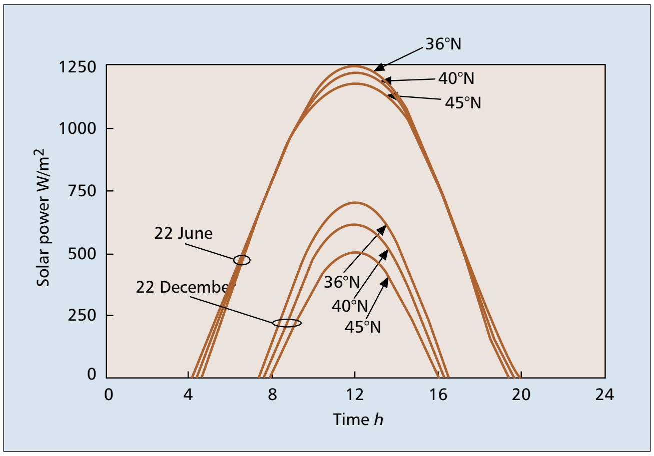


Figure 7. *Solar power flux on a HAP at an altitude of 17 km as a function of seasonal extreme, time, and latitude. (This figure appeared in [4].)*

Country/region	Acronym	Bands (GHz)
U.S.A.	LMDS	27.50–28.35, 31.00–31.30, 29.10–29.25
Venezuela	LMDS	27.50–28.50, 28.50–29.50, 31.00–31.10
Argentina	LMCS LMCS LMCS MVDS MVDS MVDS	27.35–28.35, 31.15–31.30 26.35–27.35, 31.00–31.15 25.35–26.35, 29.10–29.25 37.00–38.00 38.00–39.00 39.00–40.00
Canada	LMCS	8 → 500MHz bands 25.85–29.85
Romania	LMCS	2 → 500MHz bands 27.50–28.50
Korea	B-WLL	Several bands 24.25–26.70, 40.50–42.50
Europe	MVDS	40.50-42.50
Philippines	LMDS	3 → 1 GHz bands 25.35–28.35
Russia	LMDS	27.50–29.50

Table 3. *Frequency bands allocated for LMDS or similar services (this Table appeared in [6]).*

Percentage of time	99.99%	99.9%	99%
28 GHz	32.5 dB	12.3 dB	3.3 dB
47 GHz	64.1 dB	26 dB	7.4 dB

Table 4. *Link margins required to guarantee service for given percentages of time at an elevation angle of 30° when a Mediterranean type of climate is considered (this Table appeared in [7]).*

Key Issues

HAPs can provide quasi-stationary communication relay platforms, but several points should be examined carefully in the design of the system. For airships as well as for aircraft, the *movement* is a problem to be faced. Aircraft usually fly on a tight circle (about 2 km radius or more), while airships can theoretically stay still and they only need to compensate for the winds. The ITU has specified that a HAP should be kept within a circle of 400 m radius, with height variations of ±700 m [5], so that services are available almost all the time, while the HeliNet project has specified two position cylinders; one with 2.5 km radius and 1 km height, within which services will be available for 99.9 percent of the time, and another with 4 km radius and 3 km height, within which services will be available for 99 percent of the time. It is easier for airships than for aircraft to be quasi-stationary, but it is rather difficult to remotely control the airship's position as it is drifted by winds or pressure variations. GPS can play an important role in the precise positioning of high-altitude aerial vehicles, although it is not a trivial task. Other issues to be examined are the *aerodynamics* (the behavior of large semi-rigid structures and the thermodynamic behavior of large gas volumes cannot scale from small prototypes), the feasibility and requirements of *inter-platform links and links to satellites* (again, the effect of the platform's movement should be considered), and the link budget for platform-to-ground links and vice versa.

The choice of *energy source* is also of fundamental importance. An early design of unmanned airplanes from Jet Propulsion Laboratories (JPL) proposed the use of microwave beams emanating from the ground. However, the transmission efficiency is low, the cost of the ground station is quite high, and the radiation to other flying objects can be considerable. Another approach concerns fossil fuel, but the platform becomes heavy, and therefore expensive to be lifted and placed at an altitude. Solar energy has considerable appeal, particularly if we assume that, for either buoyancy or aerodynamic lift in the thin atmosphere, the HAP will contain large surfaces suitable for collectors. At the equatorial level, the solar power flux can reach up to 1300 W/m^2, which is quite adequate for the HAP energy source even if we assume solar cell efficiencies of 10–15 percent. However, there is always the problem that energy has to be stored for overnight use. And for increasing latitudes, during winter months the available power for overnight use will not be sufficient. Adding batteries, such as lithium-ion at about 110 Whr/kg, makes for a very large (and expensive) HAP.

Several projects have addressed the design of solar-powered long-endurance aircraft. Among them the most relevant is the study performed within the NASA Environmental Research Aircraft and Sensor Technology (ERAST) Program, which yielded the realization of a HAP prototype named Helios, which flew in August 2001, establishing a new altitude record (96,500 ft) using a completely solar-powered platform. Advanced Technologies Group proposes to supplement solar powered technology with diesel engines. The majority of the available power is consumed by the propulsion and stability system, the RF power amplifiers, and the antennas, therefore power can be used more efficiently through careful spot beam and antenna design or through power-efficient modulation/coding schemes. Airships can afford power levels similar to those of conventional fuel planes (10–20 kW) because of the large surface area on which solar cells can be deployed. On the other hand, solar-powered unmanned aircraft can have payload power less than 3 kW. Figure 7 presents the solar power flux on a HAP as a function of season, day, and latitude variations.

Spectrum Allocation

Several frequency bands have been allocated to the LMDS (Local Multipoint Distribution System) types of services (such as high-speed Internet and other data services) over 24 GHz. Table 3 presents the frequency bands allocated for LMDS or similar services. The ITU has allocated specifically for HAP services 600 MHz at 48/47 GHz (shared with satellites) worldwide (in Asia the 31/28 GHz band is assigned). HAPs can also be deployed in some 3G services (around 2 GHz). There is also a potential use of the bands in the range 18–32 GHz for fixed services. This range is allocated in Region 3 for broadband wireless applications. The sharing of the 31/28 GHz band has been examined by ITU-R extensively for Japan, and approval was obtained at WRC-2000 under operational constraints. There is a need for the 31/28 GHz band because the 48/47 GHz band is susceptible to rain attenuation, creating a serious problem in Asia and tropical regions. Table 4 presents the link margins required to guarantee services for the 28 and 47 GHz bands. In WRC2003 in June it was agreed to extend the use of these frequencies to Region 2, and currently much pressure is exercised on ITU in order to make the 31/28 GHz band available in Europe. Table 5 (an updated version of the table in [3]) summarizes the current available frequency bands for HAP applications.

Architectures and Services

Network Design

A typical HAP design should seek high reliability, low power consumption, and light payload, thus leading to an architecture that places most of the system complexity on the ground

Frequency band	Areas	Direction of the link	Services	Services to be shared with
47.9–48.2 GHz 47.2–47.5 GHz	Global	Up and downlinks	Fixed service	Fixed and mobile services Fixed satellite service (uplink) Radio astronomy band neighboring
31.0–31.3 GHz	40 countries worldwide (20 countries in Asia, Russia, Africa, etc. and in Region 2)	Uplink	Fixed service	Fixed and mobile services Space science service in some areas Space science service band (passive) neighbouring
27.5–28.35 GHz[1]	40 countries worldwide (20 countries in Asia, Russia, Africa, etc. and in Region 2)	Downlink	Fixed service	Fixed and mobile services Fixed satellite service (uplink)
1885–1980 MHz 2010–2025 MHz 2110–2170 MHz	Regions 1 and 3	Up and downlinks	IMT-2000	Fixed and mobile services (in particular, terrestrial IMT-2000 and PCS)
1885–1980 MHz 2110–2160 MHz	Region 2	Up and downlinks	IMT-2000	Fixed and mobile services (in particular, terrestrial IMT-2000 and PCS)
Region 1: Europe, Africa, Russia, the Middle East, and Mongolia Region 2: North and South America Region 3: Asia, except for the Middle East, Pacific countries, and Iran				
[1] The use of this band will be reviewed in WRC-07 after further sharing studies with fixed satellite services				

Table 5. *Current frequency bands allocated for communications via HAPs.*

segment. This is the case of a *transparent* HAP, namely a HAP that acts as a relay station, transferring information from an uplink to a downlink channel. However, a HAP can be a *processing* device incorporating a level of functionality itself (a multichannel transponder, user and feeder-beam antennas, antenna interfaces, DSP system, etc), often referred to as an On-Board Processing (OBP) system.

A general HAP architecture is illustrated in Fig. 8. ITU has proposed that footprints of a radius more than 150 km can be served from a HAP. These HAPs could cover a whole country, e.g., in [8] a structure comprising 16 HAPs was proposed for covering Japan with a minimum elevation angle of 10°, whereas in [9] it was mentioned that 18 HAPs can cover Greece, including all the islands. Fig. 9 presents the radius of the maximum coverage area versus the altitude of the HAP, as this was calculated in [10]. The lower the minimum elevation angle, the larger the coverage area but the propagation or blocking loss becomes high at the edge of the servicing area. A practical minimum elevation angle for Broadband Wireless Access is 5°, while 15° is more commonly considered in order to avoid excessive ground clutter problems. This implies that for a platform positioned at an altitude of 20 km the radius of the coverage area is approximately 200 km. Ground stations, which connect the HAP network with other terrestrial networks, can be placed on roofs of buildings. For remote areas where there is no substantial terrestrial infrastructure, satellites can be used as backhaul.

Regarding broadband applications, a *cellular architecture* (Fig. 10) with frequency reuse and cells of a few kilometers diameter provides high spectral efficiency, and hence network capacity. Fixed Channel Allocation (FCA) as well as Dynamic Channel Allocation (DCA) schemes have been examined for homogeneous and non-homogeneous traffic load per cell. Further, DCA is also particularly useful when the environment or traffic load is hard to predict. Another possible architecture discussed in the HeliNet Network [4, 11–13] is presented in Fig. 11. The platform is connected to terrestrial networks through a ground gateway, while a backhaul link can be provided via a LEO/MEO/GEO satellite system. Also, interplatform links could exist for unifying far-flung groups of people. Based on a similar architecture but without the use of satellite backhaul links, the recently commenced CAPANINA project aims to provide "broadband to all."

Several backhaul links are required to connect the HAP

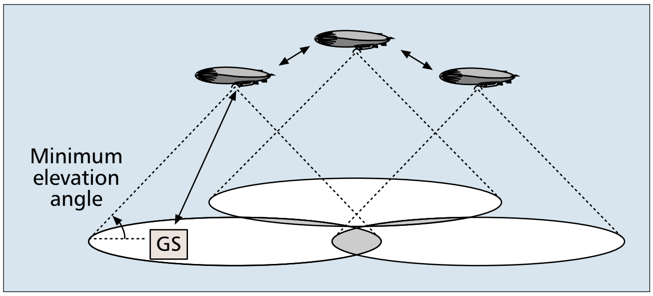


Figure 8. *A general architecture of a HAP system.*

Data rate per link (Mb/s)		
99.90%	99.00%	Clear air
240	320	320

Table 6. *Downlink data rates per backhaul link for different scenarios using the 28GHz band, assuming 5° HAP antenna, 1° ground antenna at 10km ground distance, and 50MHz bandwidth (this Table appeared in [14]).*

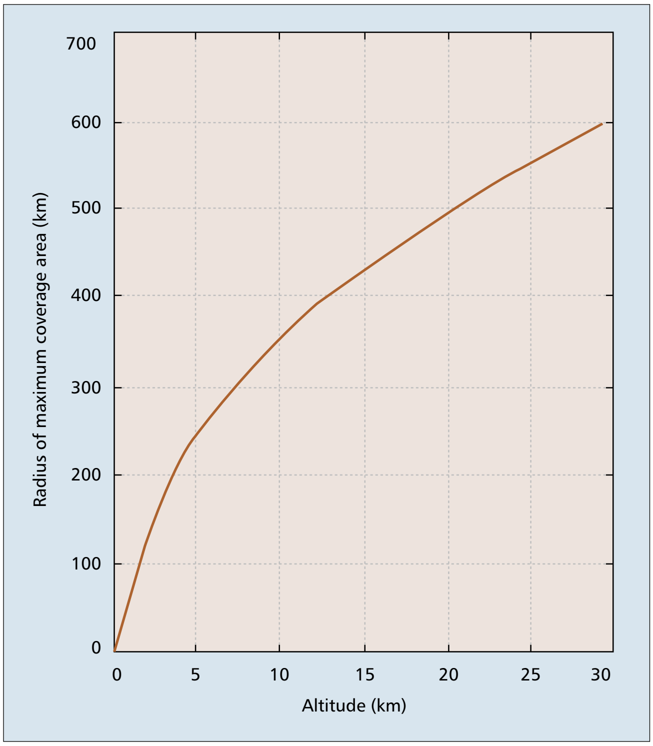


Figure 9. *Radius of the maximum coverage area as a function of the HAP's altitude.*

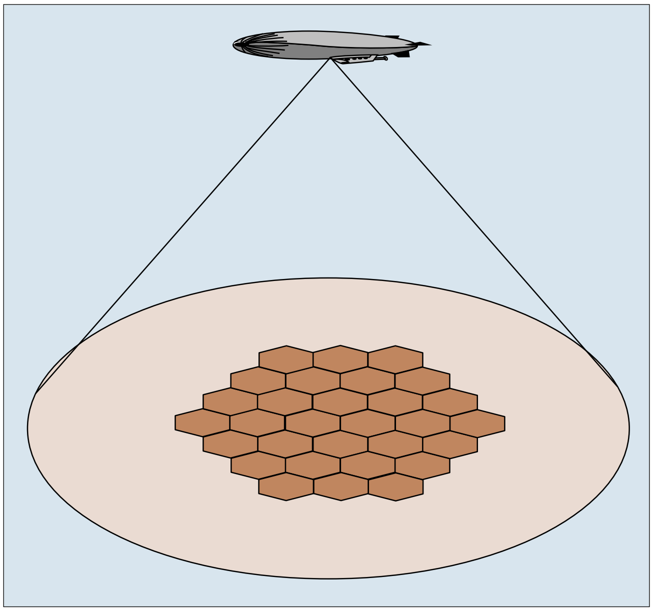


Figure 10. *A cellular architecture.*

network into a wider network. Backhaul redundancy can be proved useful in the case of a link failure. As proposed in [13] three factors can reduce the backhaul requirements (with respect to the HeliNet project):

- **Local services** — e.g., for LAN interconnection, where two users are served from the same Heliplat, and do not need to communicate significantly over the backhaul.
- **Local and/or on-board caching** — This will be useful for both video-on-demand (VOD) and Internet Web page downloads.
- **Broadcast and multicast services** — If the same transmission is sent simultaneously to n users, the backhaul requirement reduces to $1/n$ of that required from individual transmissions.

User and backhaul links are usually asymmetric [13], with the downlink carrying on average more traffic than the uplink. This means that the backhaul uplink will also carry more traffic than the downlink backhaul link. One advantage of this architecture is that multiple uplinks can be served from each backhaul station because power is not constrained for ground transmissions (assuming that there is sufficient bandwidth available). This extra capacity can be used to reduce the number of backhaul ground stations, or to increase the choice of multicast transmissions available to users, or increase the material available in the on-board caches. Regarding backhaul traffic that will be sent over a satellite, this will be further limited by both power and bandwidth constraints. Table 6 shows that for a bandwidth of 50 MHz, and for variable rate modu-

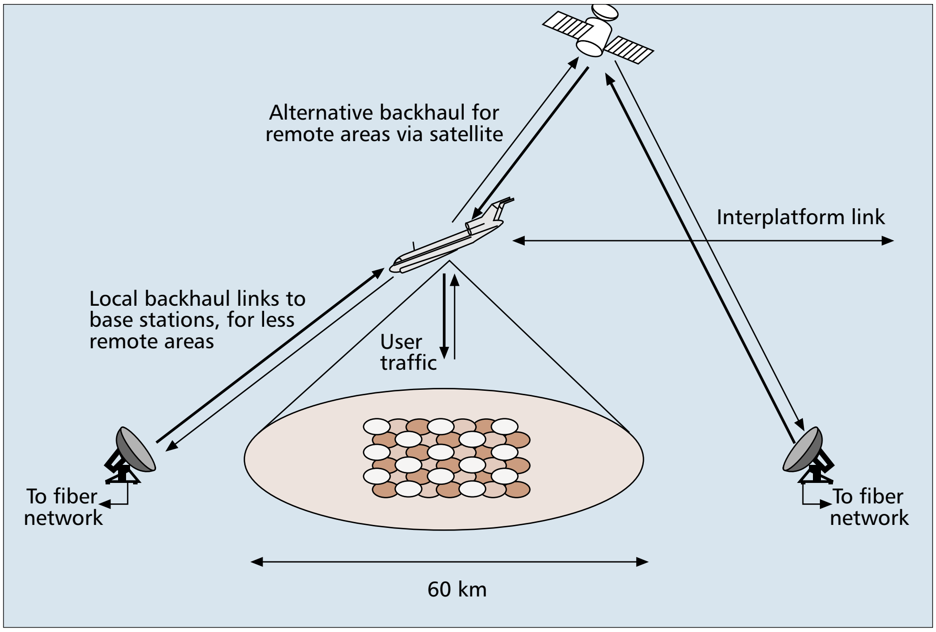


Figure 11. *The architecture scenario of the HeliNet network.*

Scenario	Number of cells per backhaul link		
	99.90%	99.00%	Clear air
Low user data rate (12.5 MHz BW)	8.0	5.3	5.3
High user data rate (25 MHz BW)	12.0	4.0	2.7

Table 7. *Number of cells served by an individual backhaul link for the 28GHz band, using a 2° steerable ground antenna at 30km ground distance (this Table appeared in [14]).*

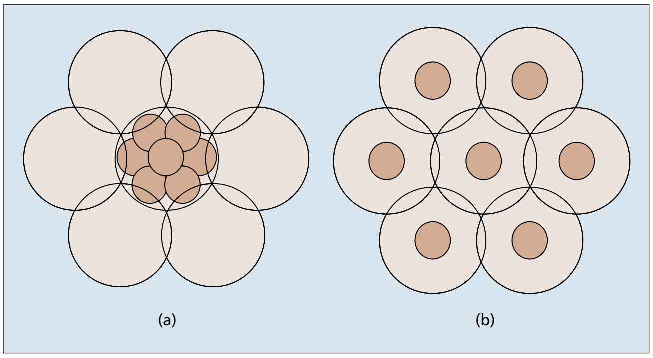


Figure 12. *Cell forming according to traffic.*

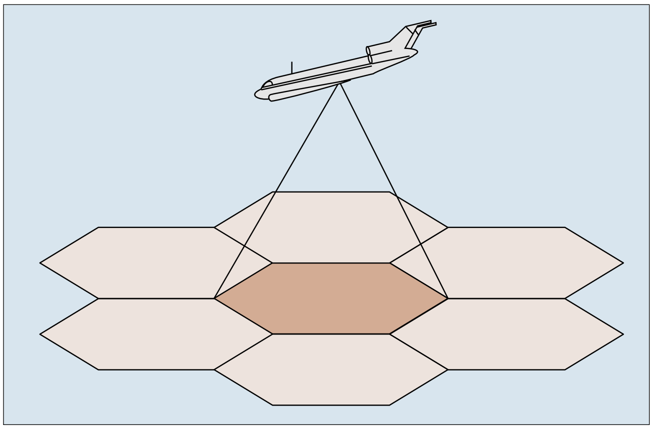


Figure 13. *The aerial cell.*

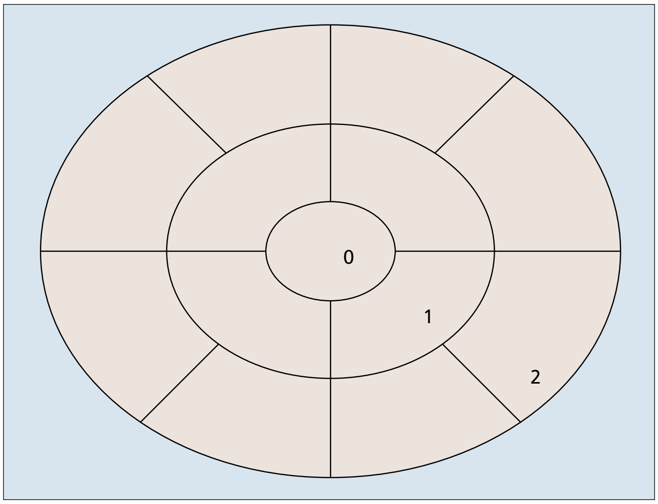


Figure 14. *Example of theoretical sectorization pattern with two outer circles.*

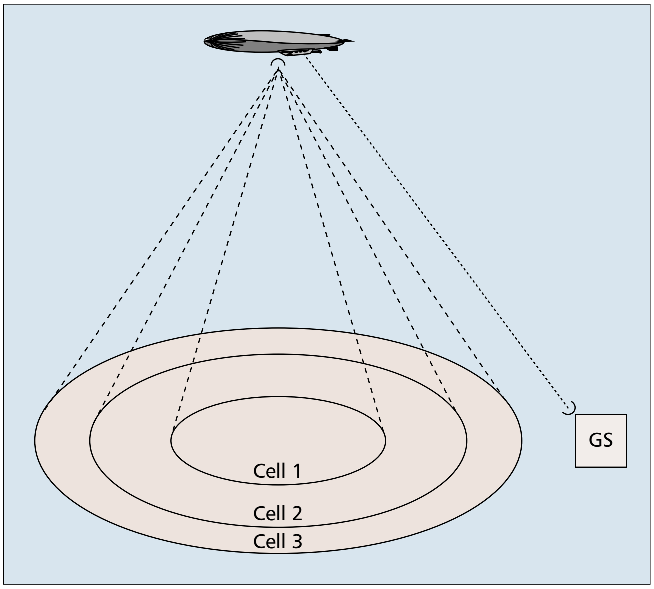


Figure 15. *Ring-shaped cells.*

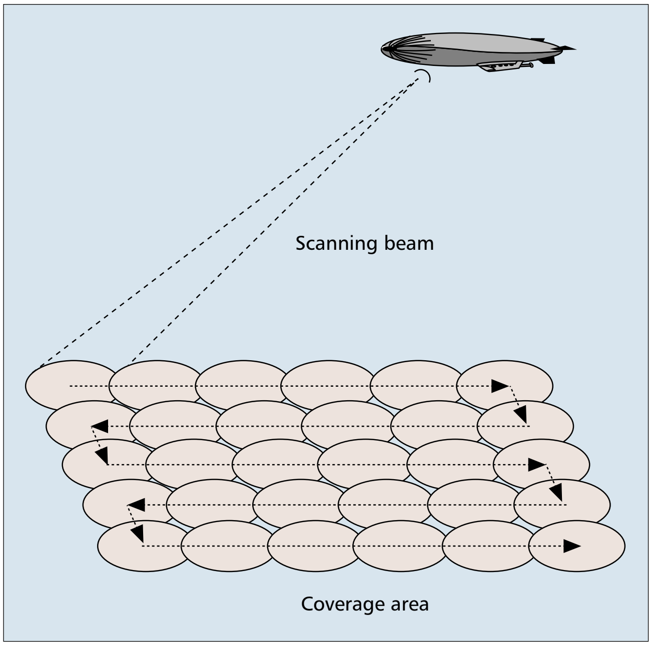


Figure 16. *Cell scanning.*

lation, the links can support data rates from 240 up to 320 Mb/s if a 256 QAM modulation scheme is used. If the 48 GHz band was used, the capacity would be reduced due to rain margin and path losses. The number of cells that can be served from a single backhaul link are illustrated in Table 7.

An architecture similar to the one presented in the framework of the HeliNet project was presented in [15]. The proposed system comprised HAPs and satellites, while optical links were employed to connect neighboring HAPs or a HAP with a satellite. The use of Dense Wavelength Division Multiplex (DWDM) technology was proposed for the optical links. Even though optical links are characterized by high transmission rates, the pointing and tracking technology for optical communications still remains rather challenging. Toward this end, the adaptation of FLEXTEC, a state-of-the-art fine pointing and tracking technology developed for optical communications in space, was proposed. FLEXTEC can enable

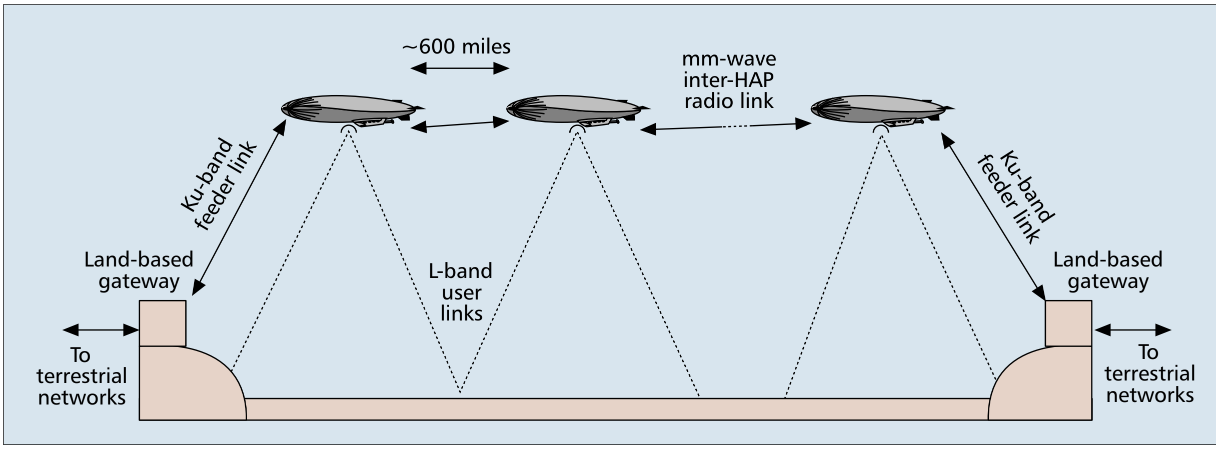


Figure 17. *A HAPs-based system for maritime services.*

maximum transmission rates through its unique two-axis tip-tilt mirror subsystem.

An architecture consisting of terrestrial, HAP, and GEO satellite layers was presented in [16]. The terrestrial layer comprised all the user terminals, as well as control and management stations. The HAP layer consisted of the set of HAPs used to cover different areas on the ground. HAPs without OBP (on-board processing) capabilities and inter-HAP links were conceived in the proposed scenario. The GEO satellite with OBP was employed to provide communications among users belonging to different HAP coverage areas. Concerning the proposed architecture, some open research issues were also mentioned.

An interesting architecture with macrocells and microcells was considered in [10]. Figure 12 illustrates a scenario with a HAP above the city center. Microcells can follow the spatial and temporal changes of traffic. In the late evening, microcells can be placed at the center of each macrocell, as presented in Fig. 12b.

In [17] the system performance was evaluated in terms of allowed traffic channels for a stand-alone UMTS rural cell served only by the aerial base station (BS), and for a rural macrocell served by the aerial BS within a cellular scheme (Fig. 13). In order to improve the system performance, a cell was divided into different sectors, with a circular sector in the center and a number of outer circles divided into sectors, as illustrated in Fig. 14. The above cases were examined in both the presence and absence of cell sectorization and always under worst-case assumptions, so four scenarios were studied. The maximum number of traffic channels was determined by the acceptable interference level. As expected, the number of available channels was greater in the stand-alone case. It was also inferred that cell sectorization increases the capacity of the system.

Another three architectural solutions were proposed in [1]. The first was called *Ring-shaped Cell Clustering* (Fig. 15) and the coverage was made up of a set of concentric rings. This simplifies the design of multibeam steerable antennas and handoff algorithms, since each cell has only one or two neighbors. The second solution was *Cell Scanning* (Fig. 16). The beam scans each cell at regular (for real-time applications) or irregular (for non-real-time applications) intervals. The traffic intended for a cell should be buffered until the scanning beam visits that cell. Likewise, the data at each user terminal should be buffered until the beam visits the respective cell. Maybe more than one beam could be used to scan cells in a staggered manner. The third solution proposed in [1] was a *stratospheric radio-relay maritime* communications system (Fig. 17). Chains of HAPs can be placed above the Atlantic ship lanes, offering typical maritime services such as voice, data, video, paging, and broadcasting.

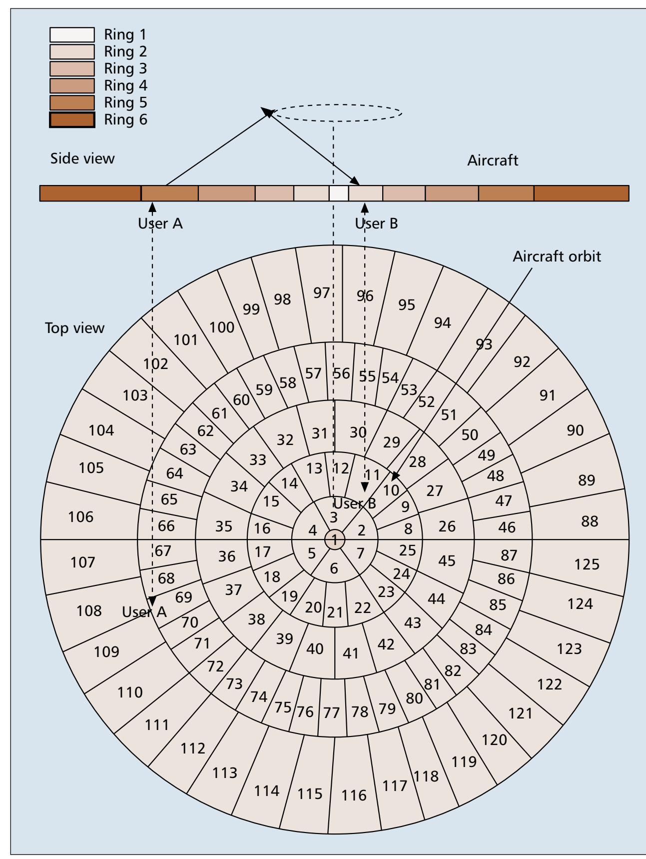


Figure 18. *The architecture of the HALO network. (This figure appeared in [18].)*

In [18] the architecture of the HALO network was discussed (Fig. 18). The HALO network architecture utilizes multiple beams on the ground, arranged in a typical cellular pattern. Each spot beam in the pattern functions as a single cell. Due to the aircraft's motion, a beam covers a cell for a specific time interval. Therefore, a beam handover may arise.

System Availability

Generally, the system availability is defined as the percentage of time for which services are not affected by outage (due to shadowing or blocking). The study in [19] proposed a new simple analytical procedure to calculate availability of HAP or satellite systems with spatial diversity. The technique was

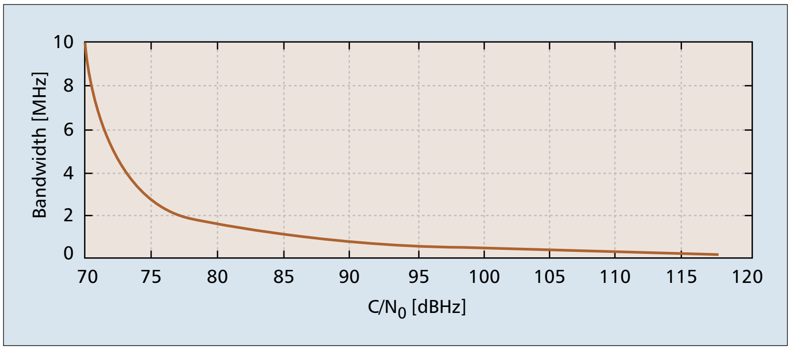


Figure 19. *Minimum bandwidth required for a 10 Mb/s user for a given* C/N_0 *(Shannon Equation* $R_B/W = \log_2(1+ C/N_0)$.) *(This is figure appeared in [6].)*

research on the technology for a stratospheric communications system in Korea was given in [20].

CAPACITY

Bandwidth is always an important design issue. In [21] and [6], the Shannon equation was solved numerically and a graph showing the required minimum bandwidth for a given *Carrier to Noise ratio* (C/N_0) for a fixed data rate is given in Fig. 19. In [14] the achievable downlink data rates per cell for different scenarios in the 28 GHz band were estimated (Table 8). A HAP user will experience intracellular interference from its serving beam and intercellular interference from the adjacent beams. By using down-link power control, the power transmitted to a user depends on the user's location (basically on the distance from the cell center). In [22] a distance-based downlink power control model was evaluated for HAP W-CDMA (Wideband — Code Division Multiple Access) systems for increasing the system capacity.

The improvement in spectrum utilization for broadband services in mm-wave bands using multiple high-altitude platforms was investigated in [23]. HAPs can never be as spectrally efficient as terrestrial broadband systems because the minimum size of their cell is limited by the maximum size of the antenna that can be accommodated on the platform. However, the user antenna can be highly directive, allowing a good spatial discrimination between HAPs in a HAP constellation. The increase of capacity for multiple platform configurations was studied in [23], and results for the scenario of one beam (cell) per HAP were given. In Fig. 20 the main HAP and one interfering HAP are shown. The performance of the single cell, multiple HAP scenario was assessed for different numbers of HAPs, different HAPs spacing radii, and user antennas with a range of directionalities. The CIR (carrier to interference ratio) was determined across the coverage area and then converted into bandwidth efficiency ($\eta \approx \log_2(1 + CIR)$). As the number of HAPs increases, CIR becomes worse. In addition, an increase in the HAPs spacing radius does not impact on CIR. As for the

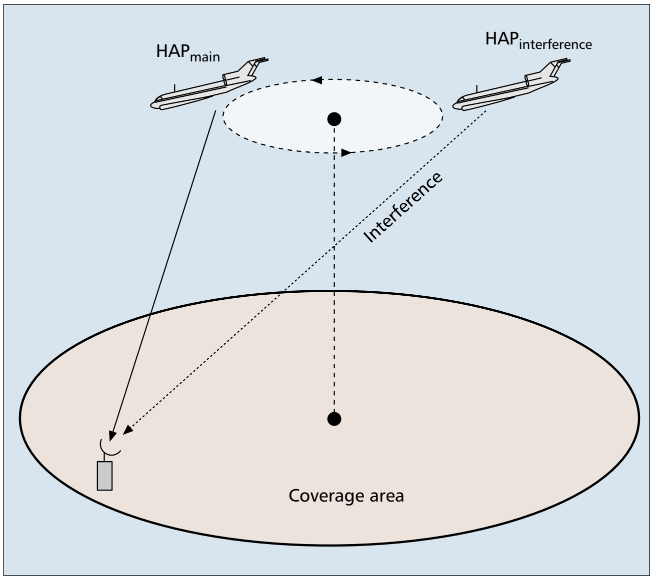


Figure 20. *Interference in a ground terminal in the case of a multiple HAPs scenario.*

based on the statistical comparison of azimuth angles of links, the elevation provided by the system, and the masking angles of the surrounding skyline. Comparative results were given for satellite-based and HAPs-based systems. A channel is available only if there are LOS (line-of-sight) conditions. The results showed that HAPs (positioned 21 km above the surface of the Earth) that have a coverage radius of about 50 km give full availability even in dense urban environments. As coverage increases, performance becomes deficient in urban areas, but one HAP is always enough for covering a large city.

SERVICES

The communication services provided by HAPs can be divided into two major categories: *low data rate services* for mobile terminals and *high data rate services* for fixed terminals. Due to their large coverage, HAPs have an advantage over terrestrial networks in two types of applications. The first is broadcasting (or multicasting). In this case HAPs present many of the benefits of GEO satellite systems providing in addition uplink channels for interactive video and Internet access. The second type of application concerns communications in areas with low population and a high need for mobile services (islands, ocean, etc.). The cost per subscriber in terrestrial wireless systems is quite high for low traffic densities because of the access points needed to cover the respective area. Hence, HAPs show a clear advantage over their competitors. Further, HAPs achieve a substantial indoor coverage at a good quality of service and at low cost.

To be immediately profitable, HAPs can be used for niche market applications, providing new services to users that are not currently served by terrestrial wireless, fiber, cable, or xDSL systems. However, as technology develops further, mass-market applications can become available soon. For instance, broadband communications from HAPs could be used to replace backhaul infrastructure for terrestrial mobile communications, especially in rural areas currently served by terrestrial microwave links.

The movement of the aerial vehicle imposes a constraint on the maximum data rate that can be transferred. For fixed stations with fixed antennas, the displacement of the HAP may cause deviation of the main lobe. The required data rate will determine the choice of steerable or fixed antennas. Useful operation is much more restricted for high elevation angles (short distances) due to the fact that the angle changes more significantly. If fixed antennas are desirable in order to eliminate cost, then a wider beamwidth antenna could be used in areas directly under the platform, while narrower beamwidth antennas would be used as distance increases. This would also lead to a gain increase as distance increases, but this will be lower than in the case of steerable antennas. Thus, many technological problems need to be solved. A good review of the

Scenario (28 GHz)	Data rate (Mb/s)		
	99.90%	99.00%	Clear air
Low rate (12.5MHz BW)	30[1]	60	60
High rate (25MHz BW)	20[2]	80	120

[1] This data rate assumes 8AMPM modulation (3 bits per symbol) and no coding with a margin of 1.1dB

[2] This data rate assumes QPSK (2 bits per symbol) and half rate coding, and as such is lower than the low bandwidth case. The margin for 8AMPM is –0.9dB, which would yield a data rate of 60 Mb/s

Table 8. *Downlink data rates per cell for different scenarios using the 28GHz band, at 30km ground distance, 2° steerable antenna (this Table appeared in [14]).*

user antenna beamwidths, the smaller the beamwidth, the better the performance. The concept was extended to a multibeam (cellular) layout from each platform, and it was shown that CIR is little affected as the number of HAPs increases while bandwidth efficiency increases almost in line with the number of HAPs.

As mentioned in both [21] and [6], the displacement of the platform introduces two problems. The first has to do with the backhaul link, which will be longer. A solution would be to have several ground stations and the HAP will connect to the one with the shortest LOS path. The second problem is that cells on the far edge of the coverage area may no longer have an acceptable link budget for practical purposes. Therefore, the maximum displacement distance should be limited so that the link budget is always sufficient. However, even though platform displacement is considered to be a problem, it may be beneficial in terms of covering spatial changes in traffic. Typically, with a HAP displacement of 6 km a saving of 3–8 percent on the minimum required bandwidth per cluster can be achieved compared to the case in which the HAP is fixed in the desired position. The level of bandwidth saving depends on the transmitter power. An increase in the transmitted power results in an increase in bandwidth saving. The results showed that the minimum received C/N_0 (on the edge of the coverage area) is worsened by the displacement, but this does not affect the peak minimum bandwidth requirements. The maximum C/N_0 (with a rain rate of 28 mm/h) is the same in all cases and achieved in the cell at the sub-platform point.

Channel Modeling and Transmission Techniques

Channel Modeling

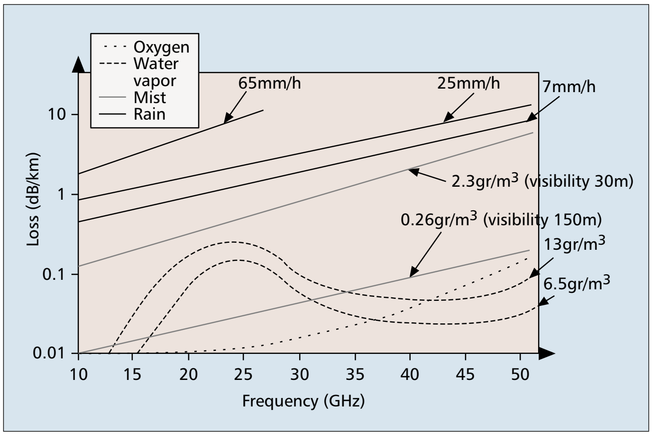
A study of wireless channel modeling and its basic parameters for terrestrial, satellite, and HAP systems was given in [1]. Propagation models aim at predicting the average received signal power at a given distance from the transmitter (large-scale propagation models), as well as the fluctuations of the received power over very short travel distances (a few wavelengths), or short time durations in the order of seconds (small-scale propagation or fading models). In built-up areas, fading occurs because there is no line-of-sight path between the transmitter and the receiver. However, even when a line-of-sight exists, multipath, which creates small-scale fading effects, occurs due to reflections from the ground or surrounding structures. It is worth mentioning that even in the case of a fixed receiver, the received power may fade due to the movement of the surrounding objects. In transmission between a satellite or a HAP and a ground terminal, propagation often takes place via many paths. A significant portion of the total energy arrives at the receiver by way of a *direct wave*. The remaining power is received by way of a *specular ground reflected wave* and the many randomly scattered rays that form a *diffuse wave*. Therefore, a signal is received from a number of different paths. The signals of the different paths are all replicas of the same transmitted signal but with different amplitudes, phases, delays, and arrival angles. Adding these signals at the receiver may be constructive or destructive.

Satellite communications links typically undergo free-space propagation, where the received power decays as a function of the transmitter-receiver distance raised to a power of two. A log-normal distribution describes the random shadowing effects that occur over a large number of measurement locations which have the same transmitter-receiver separation distance. HAP channels have many common points with satellite channels, while their path loss is much lower than in the case of a LEO satellite system. Small-scale fading is usually described by a Ricean distribution for both HAP and satellite links, although some channel models consider a Rayleigh distribution in order to describe the small-scale fading in urban areas. Some studies related to HAPs make use of satellite channel models, and the avid reader is referred to [24], which represents a thorough review of the land mobile satellite channel models. Compared to wireless terrestrial links, HAP links have more favorable propagation characteristics. In wireless terrestrial systems, the received power decays as a function of the transmitter-receiver distance raised to a power of four. Additionally, the Rayleigh distribution is commonly used to describe the small-scale fading envelope. In HAP links, there exists a dominant signal component such as a line-of-sight path, and the small-scale fading envelope distribution is Ricean. The main parameters of terrestrial wireless and HAP links are illustrated in Table 9. A critical parameter is the Ricean factor K, which is defined as the ratio of the dominant component to the scatter contribution. Typically, the range of K is 0–20 dB, and the larger its value, the higher the energy gain in HAP-based systems compared to terrestrial systems, where K is close to zero (Rayleigh fading).

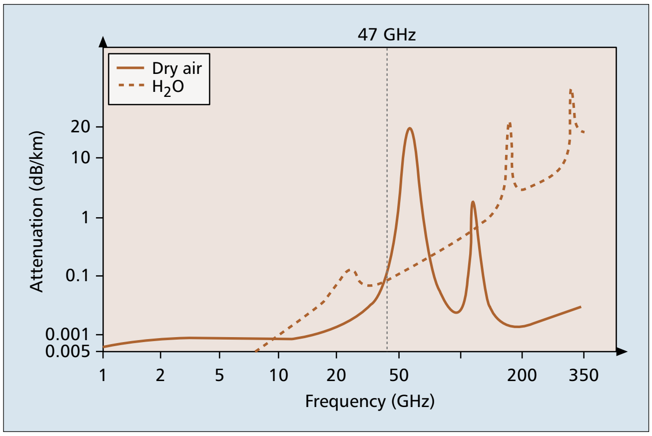
Regarding channel modeling in HAP systems, a physical statistical model for macro- and megacellular propagation was developed in [25, 26] for IMT-2000 communications systems in the S-Band (1550–5200 MHz) and validated by experimental measurements at 1.6 GHz. Particularly, in [25] a method was developed to predict the coverage area, considering the fade depth as a function of the coverage diameter for differ-

	Path loss	Fast fades distribution	Dynamic range in a cell-based system
Wireless terrestrial	r^{-4}	Rayleigh	60–80 dB (40–50 dB due to propagation-induced difference and 20–30 dB due to fading)
HAP	r^{-2}	Ricean	12–22 dB (2 dB due to propagation-induced difference and 10–20 dB due to fading)

Table 9. *Basic wireless terrestrial and HAP channel parameters.*



■ **Figure 21.** *Attenuation due to rain, mist, water vapor, and oxygen as a function of the frequency.*



■ **Figure 22.** *Attenuation due to dry air and H_20 as a function of the frequency.*

ent outage levels. The model proposed in [26] was built on the advantages of both physical and empirical models. It was shown that the model performed well in analyzing polarization (MIMO) multiplexing schemes because of its physical background.

In [27] a study of small-scale fading for a communication link at 2GHz between a terrestrial user (fixed or mobile) and a HAP was carried out in the presence of scatterers on the terrain. The analysis was based on a theoretical model for terrestrial links which was extended to the HAP-based system.

A channel model based on a semi-Markov process was proposed and analyzed in [28]. Both a two-state and a three-state channel were assessed. The two-state channel model was used to describe "good" (Ricean fading) and "bad" (Rayleigh fading) channel conditions, while in the three-state channel model, the first state described the LOS condition (Ricean distribution), the second state represented the shadowed condition (Rayleigh-Lognormal distribution), whereas the third state denoted the condition when the radio propagation is completely blocked (Lognormal distribution). Obviously, the three-state channel model allows a better approximation of the received signal compared to the two-state model.

Generally, the movement of the aerial vehicle or the mobile terminal results in a Doppler shift in frequency. In [29] this point was examined for the case of the platform acting as a GSM base station. A more complete channel model was derived including the Doppler effect and taking into account the directivity of the on-board antenna.

Rainfall rate (mm/h)	Climate zone	Typical regions
8	A	Desert
19	D	USA (California)
28	F	UK
42	K	USA (Great Lakes) North India

■ **Table 10.** *Rainfall rates for different climate zones which are exceeded for 0.01 percent of the time.*

Rain Effects

Although rain attenuation effects are negligible at the range of 2 GHz, they are predominant at higher frequencies, especially above 20 GHz. The higher the frequency, the higher the attenuation and the impact on QoS. Figure 21 illustrates the attenuation in dB/km due to rain, mist, water vapor, and oxygen, while Fig. 22 presents the attenuation due to dry air and H_2O. Rain effects were studied in [6, 13, 30]. Rain attenuates the signal by scattering or absorbing radiation. In [13] it was mentioned that for HAP availability of 99.9 percent and above, rain is the dominant attenuation factor at 28 GHz and above. Other factors, such as clouds, water vapor, oxygen, and scintillation, offer less variability and hence do not contribute at availabilities above 99 percent. Rain attenuation (in dB/km) can be expressed as

$$\gamma_R = kR^\alpha \tag{1}$$

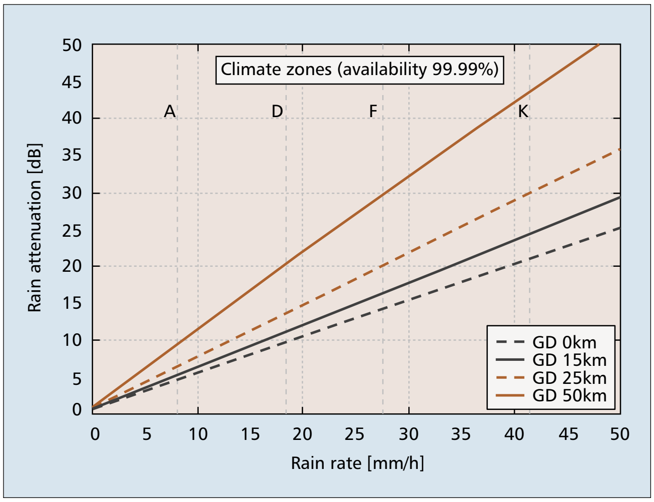
where R is the rain rate (mm/h). The values of k and α can be obtained from ITU-R PN 838-1 and depend on climatic zone and transmission frequency. Table 10 lists some rainfall rates which are exceeded 0.01 percent of the time for different climate zones [31]. The predicted attenuation along a slant path L_s, taking into account a slant path reduction factor r is given by

$$A = \gamma_R L_s r \tag{2}$$

$$\text{where } r = \frac{1}{1+\frac{L_G}{L_0}} \tag{3}$$

and L_G is the corresponding horizontal distance relating to the slant path and $L_0 = e^{-0.015R}$ [32]. In [6] the rain effect at 30 GHz for different ground distances was studied and Fig. 23 shows the results. A comparison was given for two scenarios: one with a ground base station (GBS) and one with a platform base station (PBS). In the case of a PBS, the signal is not traveling through rain for long, as rain occurs in the first few kilometers of the atmosphere. However, for the case of a GBS, the signal travels through rain for the whole distance of the path. For each scenario and for different climatic zones there is a crossover point in the received power which determines the best solution. A study of the link outages as a function of rainfall was given in [33]. Rain variability is also of interest and studies [34, 35] introduced a rain attenuation correction factor for the variability of rain with altitude, taking into account the rainstorm type.

Strategies for ameliorating rain effects were discussed in [13, 30, 36]. Space, time, and frequency diversity were studied in the HeliNet project. As far as space diversity is concerned, an optimal separation distance between ground stations exists. As it was mentioned in [7], this is rather different from the case of satellite links, in which there is no significant increase in path length, and thus in attenuation, with distance from the center of the coverage area, giving no optimum separation distance. The main goal is to avoid a localized rain outage.



■ **Figure 23.** *The effect of rain on signal attenuation at 30 GHz for ground distances 0–50 km. Vertical lines indicate rain rates for typical climate zones that must be tolerated to achieve an availability of 99.99%. (This figure appeared in [6].)*

Different diversity methods can be assigned to different traffic and user categories. Studies [13, 30] focused on the effect of the antenna beamwidth on the rain scattering interference, for transmission at 28 and 48 GHz. The problem is illustrated in Fig. 24. In [36] it was mentioned that an increase in the signal power may overcome rain attenuation but does not reduce interference, whereas an increase in the number of reuse channels reduces interference by reducing the number of neighboring co-channel cells affected by rain.

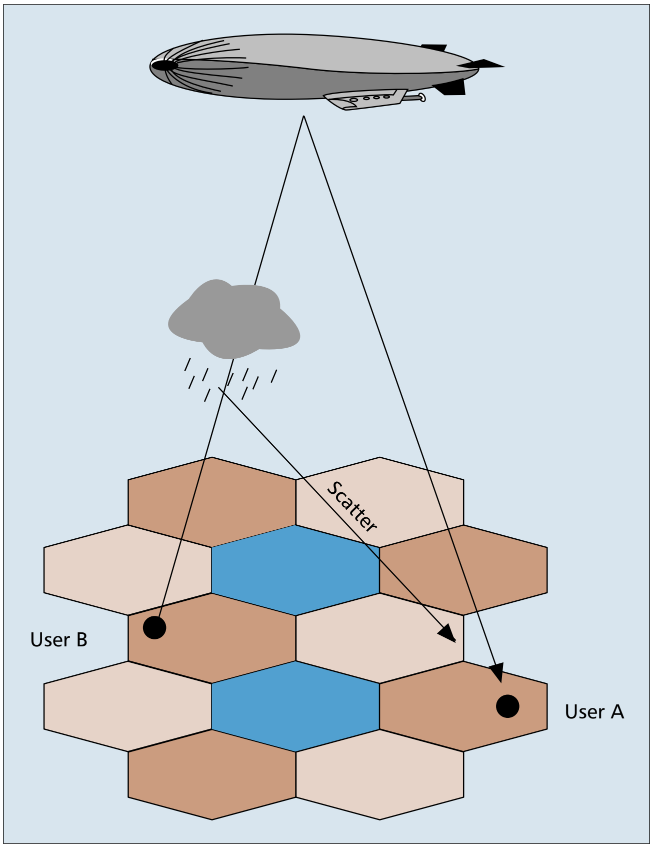
Penetration Loss

Although the issue of outdoor to indoor propagation has been well examined for the case of satellite and terrestrial systems, this issue has been scarcely addressed in the literature for communication links at high elevation angles, which is the case with HAP systems. A study [37] examined the relation between the building penetration loss and elevation angles of a HAP for the range of 2 GHz. The mean penetration loss for a target building for elevation angles from 60° and above was calculated, both for the ground and first floor. As expected, the penetration loss was smaller on the first floor, leading to the conclusion that the penetration loss is an increasing function of the elevation angle.

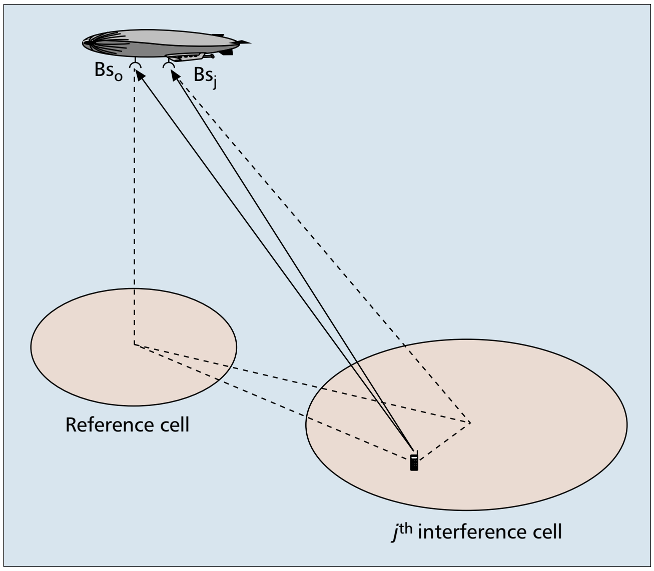
Interference Analysis

Interference is a very important issue in any communication system. In a HAPs-based system interference is caused by antennas serving cells on the same channels and arises from overlapping main lobes or sidelobes. We can discriminate two kinds of interference: interference originating from users of the HAP-based network and interference from/to terrestrial or satellite systems sharing the same or adjacent frequency bands. Considering the first case it is worth mentioning the differences in interference levels between terrestrial and HAP networks. Terrestrial systems are generally interference limited, but it is difficult to predict the interference levels from place to place as they strongly depend on terrain and building patterns. In contrast, propagation in HAPs systems is achieved mainly through free space, thus the interference levels can be predicted quite successfully.

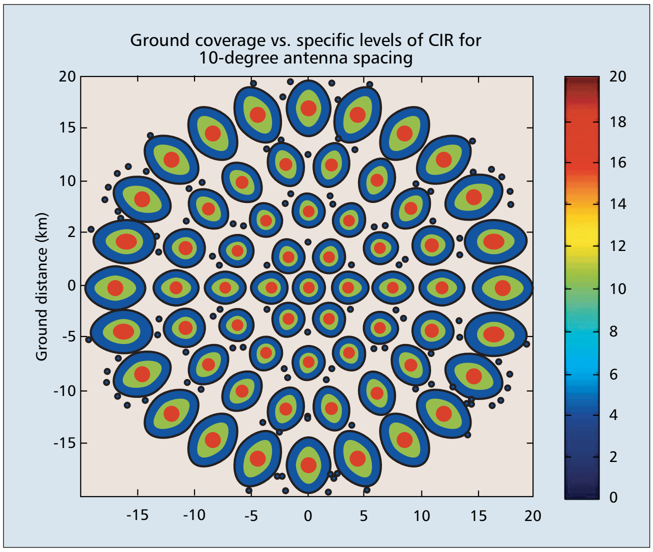
In [38] the other-cell-to-same-cell interference factor *f*, for the reverse link of a power controlled HAP CDMA system, was evaluated (in CDMA systems the reverse link capacity is limited by interference by users in the same cell or in other cells). The HAPs uplink interference geometry is illustrated in Fig. 25. The reference cell is considered to be located directly below the platform, served by the station BS_0. A mobile station in the jth cell is served by BS_j, but at the same time it produces an interference power to BS_0. It was shown that the other-cell interference is largely dependent on the first four tiers of the surrounding cells.



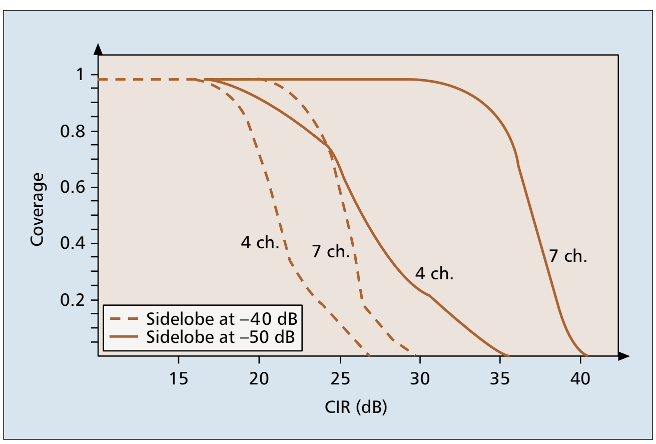
■ **Figure 24.** *Geometry of rain scattering. The radiation beamed toward user B is scattered by the rain and causes co-channel interference to user A, who is located in another cell.*



■ **Figure 25.** *HAPs uplink interference geometry.*



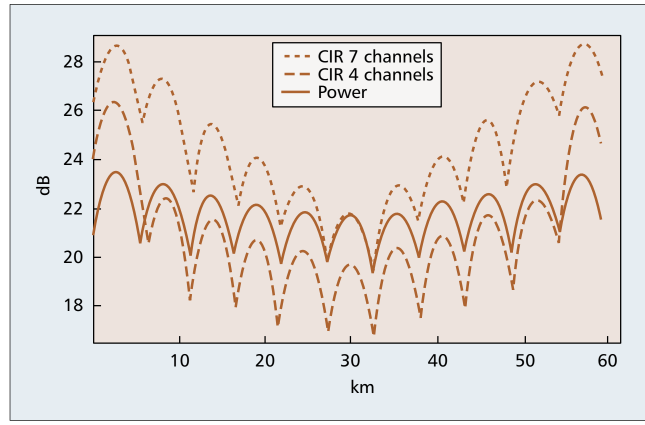
■ **Figure 26.** *|sinc^{3}βx| antenna performance. Total ground coverage for a 10-degree boresight separation angle of co-channel antennas. Coverage is dependent on the required ground CIR. The white areas indicate CIR below 0 dB. (This figure appeared in [39].)*



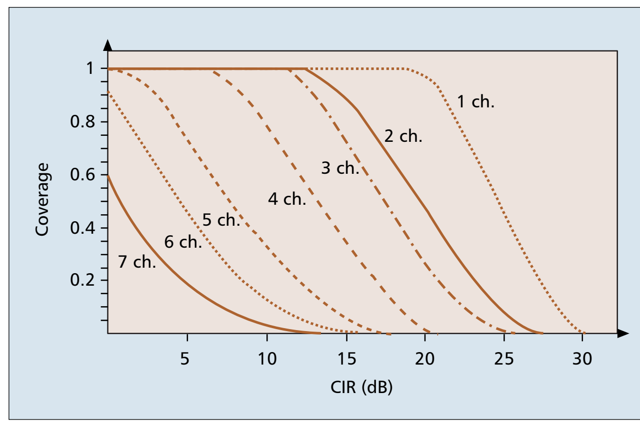
■ **Figure 27.** *Effect of sidelobe level on coverage for one of four and seven channels. (This figure appeared in [40].)*

The effects of the antenna specifications on CIR and thus on QoS were investigated in [36, 39, 40]. Key equations for determining the CIR for differently spaced antenna profiles were derived in [39]. In particular, two symmetric antenna profiles were compared, a |sinc^{3}βx| approximation (horn antenna) and a patch array antenna profile. Figure 26 shows that the footprint size and hence ground coverage is seen to depend heavily on the required level of CIR. It was shown that for differently spaced boresight separation angles there is a maximum achievable CIR value, because of the interfering antenna sidelobes. The patch antenna profile performed similar to the |sinc^{3}βx| profile, but the increased sidelobe interference caused a reduction in the total coverage. Also, the number of frequencies required to deliver 100 percent coverage was increased.

Studies [36, 40] concentrated on two different channel reuse schemes: one with four channels and another with seven channels. When few channels are reused, the cell edges suffer interference from neighboring main lobes, while sidelobe suppression reduces interference only at the center of the cell. However, when more channels are reused, the angular separation between co-channel cells is greater and the interference

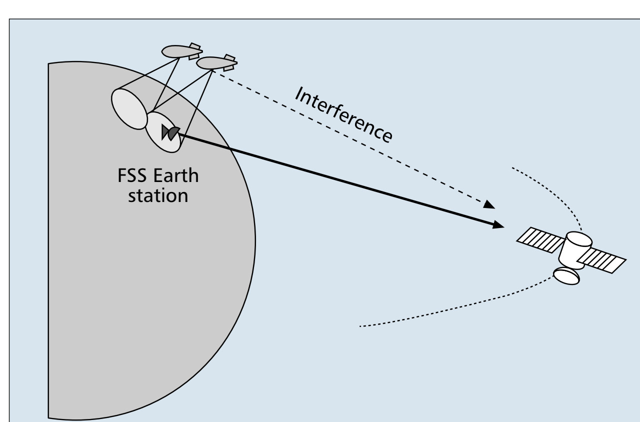


■ **Figure 28.** *CIR profile through center of service area for sidelobes at –40 dB. (This figure appeared in [36].)*

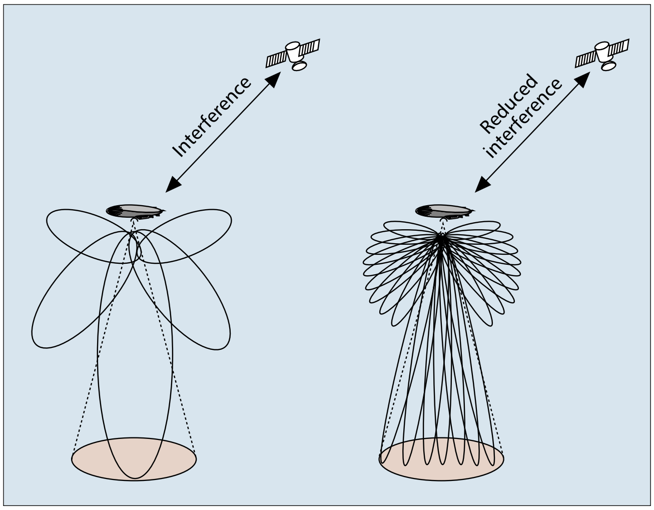


■ **Figure 29.** *Geographical channel overlap shown as multichannel coverage. (This figure appeared in [40].)*

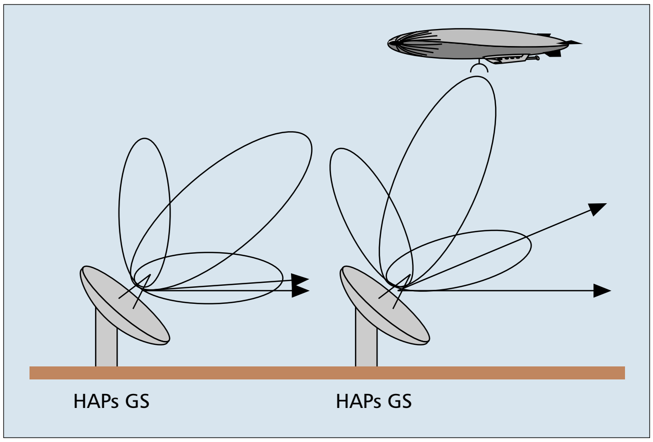
is reduced for the majority of the coverage area. This means that for a certain CIR threshold, the scheme with seven channels achieves a greater coverage area. In other words, when for the four-channel scheme there is not multichannel coverage at the cell edges, the seven-channel scheme presents multibeam coverage, which can be useful for a handoff mechanism. Figure 27 illustrates the fractional simultaneous coverage for the cases of –40 and –50 dB sidelobe levels, Fig. 28 presents the CIR profile through the center of the coverage area for sidelobe at –40 dB, while in Fig. 29 the geograph-



■ **Figure 30.** *Interference from HAPs to a GEO satellite.*



■ **Figure 31.** *Improvement of the radiation pattern of an on-board antenna by beam shaping.*



■ **Figure 32.** *Increase of the minimum operational elevation angle.*

ical channel overlap is shown as multichannel coverage for the cluster of seven cells.

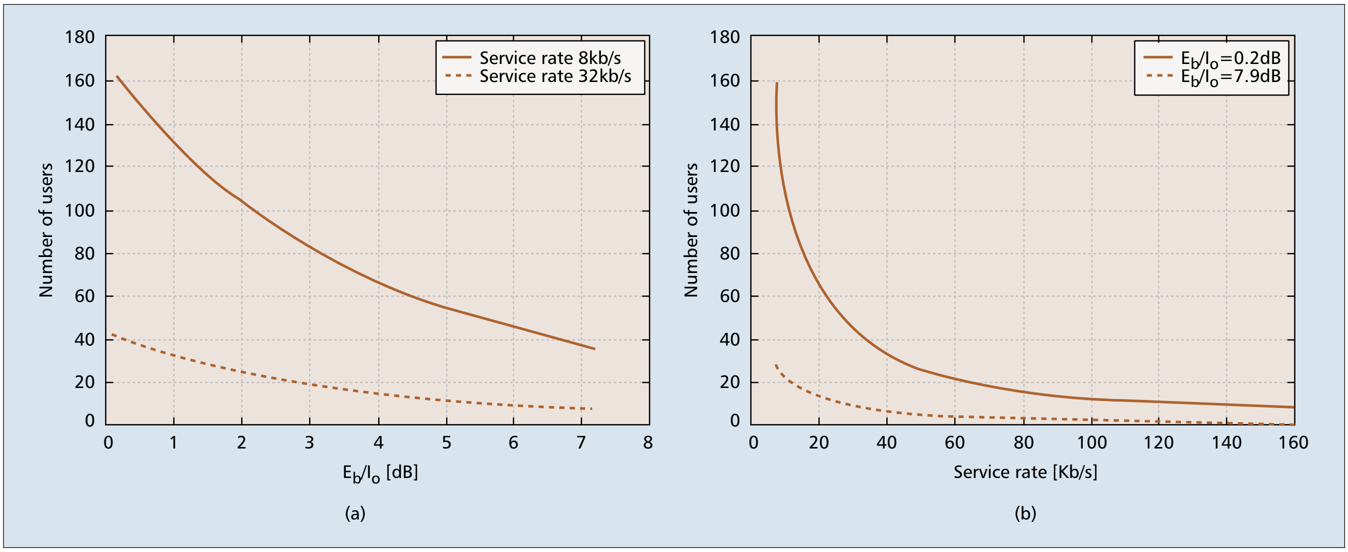
Regarding interference from/to other systems, we can distinguish the following cases of interference paths: between HAPs ground stations and other terrestrial stations or satellite earth stations; between HAPs ground stations and space stations, i.e. satellites; between HAPs on-board stations and other terrestrial stations; and finally between HAPs on-board stations and space stations. Studies [9, 41] dealt with the interference from a HAPs-based network to a GEO network (Fig. 30) and the interference from a GEO Earth station to a HAP gateway. The authors in [41] investigated the interference at 31/28 GHz in Japan, while in [9] the interference at 47 GHz was examined for a potential use of HAPs in Greece. Both studies showed that the interference level was acceptable in both scenarios. Moreover, in [42, 41] interference mitigation techniques were presented. It was shown that the interference to GEO services can be reduced by improving the radiation pattern of the on-board antenna by beam shaping (Fig. 31). While for the case of HAPs ground stations interfering with other ground services, the minimum elevation angle could be increased (Fig. 32). A mitigation technique was described in [42] that is a modified Maximal-Ratio-Combining (MRC) beamformer for on-board digital beamforming (DBF). It was shown that as the sidelobe level of the antenna decreases the BER performance improves.

The interference levels always affect the supported number of users. Calculations of the number of users versus E_b/I_o, that is, the bit energy per interference Power Spectral Density (PSD in Watts/Hz), for different service rates were carried out in [10]. Figure 33 presents the minimum number of users for a UMTS HAP station.

A UMTS coverage planning using a HAP station was performed in [43]. The fade margin, namely the amount by which a received signal level may be reduced without causing system performance to fall below a specified threshold value, was calculated for different elevation angles and outage probabilities by using an empirical model. Then the interference factor f was calculated for both uplink and downlink and for different isoflux footprints.

Transmission and Coding

Transmission/coding techniques have always constituted an issue of paramount importance in every communication system. The HeliNet project aimed at the evaluation of linear and non-linear modulation schemes (QPSK, QAM, M-APSK (starQAM), CPM, GMSK, and MA-MSK). The modulation schemes were evaluated in the non-linear region of the transmitted power amplifier. Suitable Forward Error Correction (FEC) coding



■ **Figure 33.** *Minimum number of users with UMTS CDMA. (These figures appeared in [10].)*

	Modulation and coding	Max. Bit rate per cell	Availability	Internet access (60 Mb/s)	Video-on-demand (36 Mb/s)	Video-conference (18 Mb/s)	Telephony (6 Mb/s)
Option 1	64-QAM uncoded	120 Mb/s	Clear air	✔	✔	✔	✔
Option 2	16-QAM uncoded	80 Mb/s	99.0%	✔	✔	✔	✔
Option 3	16-QAM coded	55 Mb/s	99.90%	~	✔	✔	✔
Option 4	GMSK coded	23 Mb/s	99.90–99.99%	✘	✘	✔	✔

✔ Service can be supported at full data rate
~ Service may be supported at reduced data rate
✘ Service cannot be supported

Table 11. *Four transmission options and their suitability for broadband services (this Table appeared in [7]).*

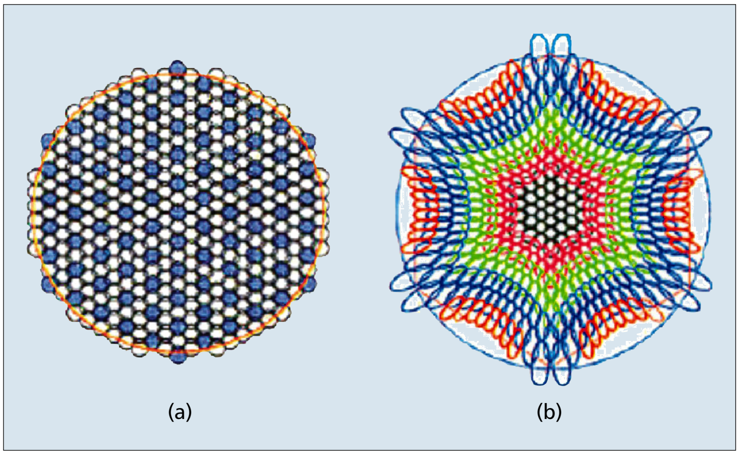


Figure 34. *Typical examples of multibeam footprints proposed in the ITU-R recommendation: a) elliptical-beam uniform footprint model (367 beams); b) circular-beam multizone footprint model (397 beams).*

schemes should be identified for each type of service, always with respect to delay, BER, and computational cost. Convolutional codes, turbo codes, product codes, and RS codes were also examined in the framework of the HeliNet project. Regarding synchronization, this should include both carrier and symbol timing correction. If we take into consideration that fast fading does not impose a serious problem in the case of HAPs, coherent demodulation may be applied. Furthermore, although equalization is usually not essential, it can prove useful in the case of low elevation angles. In [6] the case of adaptive modulation schemes was considered. These schemes are particularly effective for power-limited aerial vehicles, namely solar-powered unmanned vehicles. It was mentioned that a higher-order modulation scheme can be used in clear air conditions, such as 8-PSK, which will increase the data rate by 50 percent, so that additional lower availability services can be supplied. It was also mentioned that the power budget can be reduced further (by approximately 4 dB) if a rate 1/3 turbo code is used. The key objective is to develop a range of modulation/coding schemes, suitable to serve the broadband telecommunication services (with specified QoS and BER requirements), applicable under different attenuation conditions. These will range from low-rate schemes involving powerful FEC coding when attenuation is severe, up to high-rate multilevel modulation schemes when channel conditions are good.

An interesting approach is the use of adaptive coding and modulation based on channel conditions. Due to the centralized nature of the HAP, the base station on board the HAP is aware of the channel losses to the subscribers, and can select the most appropriate modulation and coding scheme. The modulation parameters can be controlled either dynamically, i.e. slot-by-slot, and can be changed during the connection, or they can be assigned at the call setup and remain invariable during the call duration. A bandwidth-efficient coding and modulation scheme can be used for LOS conditions, whereas power-efficient schemes can be employed to counteract shadowing. The adaptive coding and modulation schemes can be combined with space and platform diversity techniques, yielding an increased system throughput and a more reliable system, especially in the case of providing broadband services to passengers in high-speed public transport vehicles.

Investigation of power- and bandwidth-efficient coding and modulation schemes were conducted in the framework of the HeliNet project. Three modulation schemes were examined for low, medium, and high data rate applications: GMSK, 16-QAM, and rounded 64-QAM, respectively. Besides the modulation schemes, two concatenated coding schemes were also developed. Table 11 shows the suitability of four transmission options that are based on the aforementioned modulation and coding schemes

In [44] the applicability of Space-Time Block Codes (STBC) was studied for communications via HAPs. The principle of STBC is to provide two or more statistically independent channels for transmission or reception of the same information. Both the transmitter (HAP) and the receiver (mobile station) had two antennas, while the channel was simulated using Lutz's model. (For more information on this model refer to [24].) The modulation scheme considered was QPSK, and BER performance evaluations were presented for uncoded and STBC signals, for both urban and open areas. As expected, the STBC scheme presented an enhanced performance compared to the uncoded scheme.

The application of concatenated coding, comprising a Reed Solomon encoder, interleaving, and a convolutional encoder, was evaluated in [45] for a DQPSK modulation scheme. The performance of the system was assessed for different values of the user's elevation angle by the commonly used Bit Error Rate (BER) vs. E_b/N_0 diagrams. In the simulation a Ricean fading model was used whose K factor was a function of the elevation angle. As the elevation angle decreased, the K factor was reduced, resulting in Rayleigh fading for elevation angles smaller than 12°. Obviously, the smaller the elevation angle, the worse the performance of the system.

Antennas

The antenna system is one of the most important performance factors in a HAP configuration. In [3, 8] the required functions for a successful broadband HAP antenna were summarized in the rules:

- Use of high radio frequency in order to secure a sufficient bandwidth.
- Directional antenna with a high gain to cope with attenuation in high frequencies. As mentioned above, co-channel cells are interference limited by antenna beam overlap. Minimization of interference can be attained by sidelobe minimization. Beam-forming can use either phased-array antennas or lightweight, possible inflatable parabolic dishes with mechanical steering.
- A multibeam antenna that accommodates 100 beams or more, both for transmission and for reception, to cover views as wide as 120° or more from the stratosphere with a high gain and to achieve effective use of the frequencies involved. ITU-R typical examples of multibeam footprint pattern for broadband access, each of which has 300–400 cells in the Ka band, are shown in Fig. 34. In Fig. 34a footprints on the ground form a circular pattern of the same size, regardless of the direction and the elevation angle, while the cross-sections of the antenna beams are elliptical. Further, in Fig. 34b a model is given where a service area is divided into several zones, according to the elevation angle, so that the beam gain in each zone is constant, hence the footprints become necessarily elliptical.
- Cancellation of the influences of altitude/position variations of the HAP on the footprint on the ground by means of beam control.
- Reduced weight, size, and power consumption of the mission payload.
- Must operate reliably in the stratospheric environment.

Considering the movement of HAPs we see that it is necessary to compensate this movement by mechanical or electronic steering. A serious constraint is the available payload aperture. As the size of cells decreases, their number increases and also the required payload aperture increases. The structure size of an antenna array was calculated in [10] as a function of the radius of the central cell (broadside cell), for a platform at 21 km operating at 2.2 GHz (Fig. 35). The size of the antenna array is also determined by the altitude of the platform for a specified radius of the central cell. As the altitude of the platform increases, the size of the array also increases. However, the higher the operating frequency, the smaller the array.

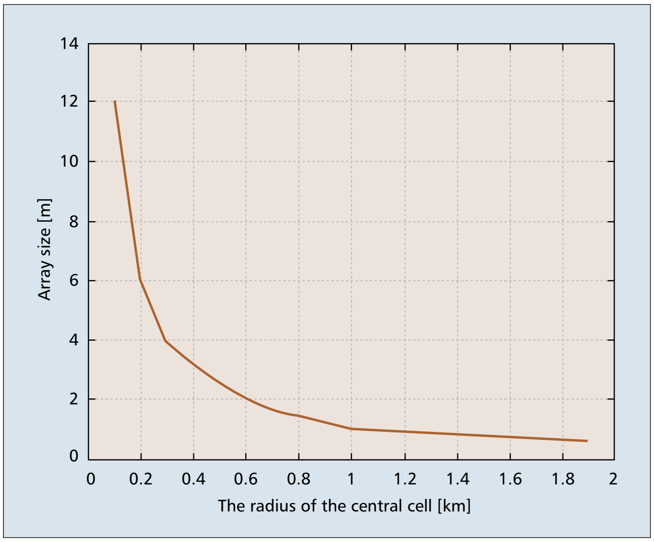


Figure 35. *The size of a square array antenna as a function of the radius of the central cell for a HAP operating at 2.2 GHz and at an altitude of 21 km. (This figure appeared in [10].)*

Two types of multibeam antennas meeting the above requirements were described in [3, 8, 46]: a Multibeam Horn (MBH) antenna of the mechanical-drive type for operation at 48/47 GHz, and a Digital Beamforming (DBF) antenna of the electronic-scanning type for operation at 31/28 GHz. Basic configurations of the antennas are shown in Fig. 36, and the basic specifications of the respective antennas are presented

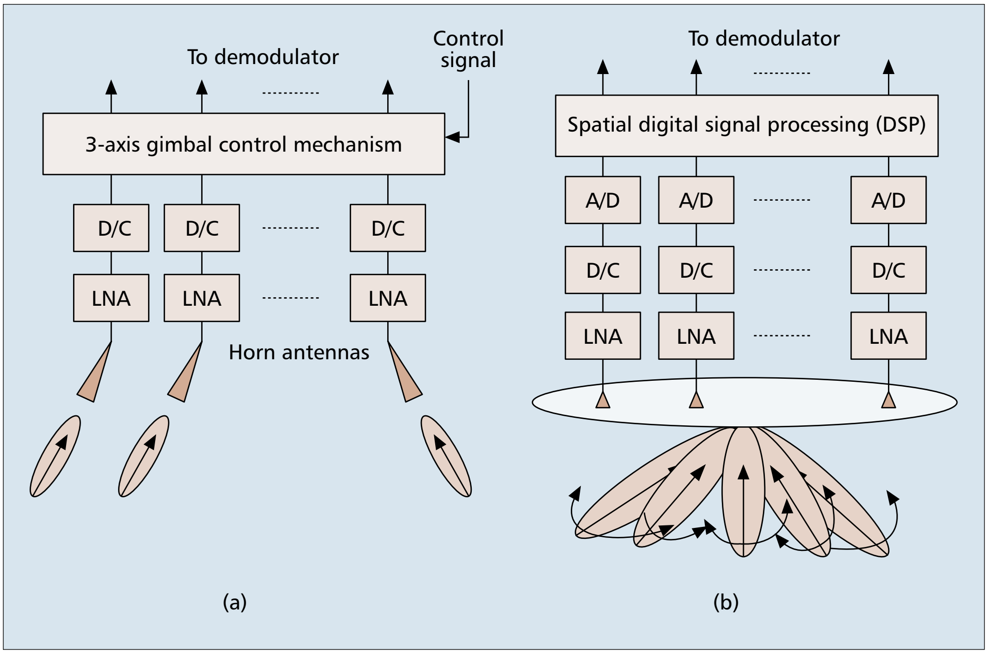


Figure 36. *Basic configuration of prototype multibeam antennas (in case of receiving): a) multibeam horn (MBH) antenna; b) digital beamforming (DBF) antenna. (This figure appeared in [3].)*

Item	MBH antenna	DBF antenna
Frequency band	T_x 47.2–47.5 GHz R_x 47.9–48.2 GHz	T_x 27.5–28.35 GHz R_x 31.0–31.3 GHz
Antenna type	Seven corrugated horns	16 (4×4) patch array
Spot beamwidth	12°	10° ~ 13°
Number of beams	Seven fixed beams	Nine fixed beams; three tracking beams
Bandwidth	300 MHz or more	4 MHz
EIRP	6.3 dBW or more	11 ~ 15 dBW
G/T	–15.4 dB/K or more	–13 ~ –17 dB/K
Compensation for platform fluctuation	Position sensor and three-axis gimbal control mechanism	Adaptive beamforming with spatial digital signal processing
Transmission bit rate	56 Mb/s	4 Mb/s
Power consumption	1.0 kW or less	1.6 kW or less
Weight	150 kg or less	74.2 kg
Others	Frequency reuse factor: 7 or less Isolation between co-channel beams: 30 dB or more	Sampling rate: 32 MHz Resolution: 12 bits DSP device: FPGA (R_x: 100 k gates × 61; T_x: 100 k gates × 31)

Table 12. *Main specifications of the multibeam antenna prototypes (this table appeared in [3])*

in Table 12. In [3] it was mentioned that the prototype antennas were developed as limited-function redundant models, which permitted evaluation and demonstration of the concept, and photographs of the antennas are seen in Fig. 37. Recently, in the framework of the national Japanese "SkyNet" project, the basic functions of the MBH and DBF antenna systems were successfully tested, using a helicopter, while it is anticipated that in the future, an experiment will take place in the stratosphere using an unmanned airplane.

The main features of the MBH antenna [3, 8, 46] are the broad bandwidth (depending on existing technology), the excellent wide-angle characteristics of gain and axial ratio, and the comparatively low development expense. The footprints of this antenna are fixed cells, so using a different frequency for each beam results in four or seven frequencies in the spatial domain. Furthermore, the antenna must feature a sufficiently low side-lobe level. Considering the movement of a ground user terminal or the drift of the HAP (due to variations in atmospheric pressure or wind), it is obvious that a handoff action becomes necessary. With this antenna, each element requires an aperture, as each element acts as a directional antenna. When the antenna is composed of a few dozen or hundreds of elements, the antenna becomes oversized, and the number of cables connecting the repeater and the respective antenna also increases, making the gimbal difficult to rotate because the Radio Frequency (RF) cables may be twisted. Therefore, this antenna is considered not to be particularly suitable for a large-scale multibeam antenna application. To overcome the twisted cable problems, an improved mechanical control mechanism was developed. It employed individual steering mechanism for each of the horn antennas instead of the gimbal control mechanism in order to keep the footprint of the beams fixed even with the platform rotation in the horizontal plane. The steering motions of the antennas were linked to each other, so that only one motor could drive all the antennas in the horizontal plane in principle. Generally, this antenna lacks flexibility, relative to the DBF antenna discussed below.

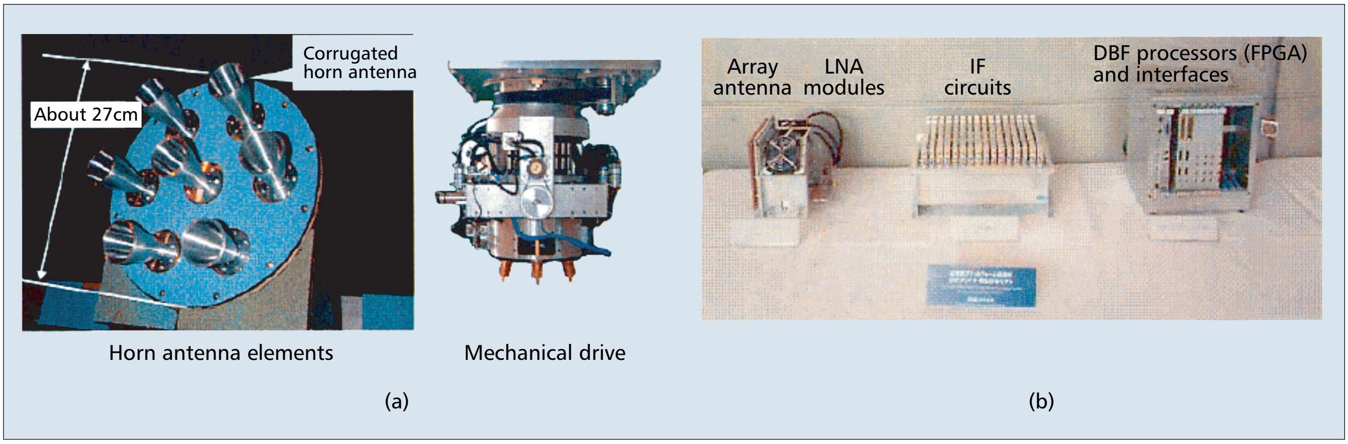
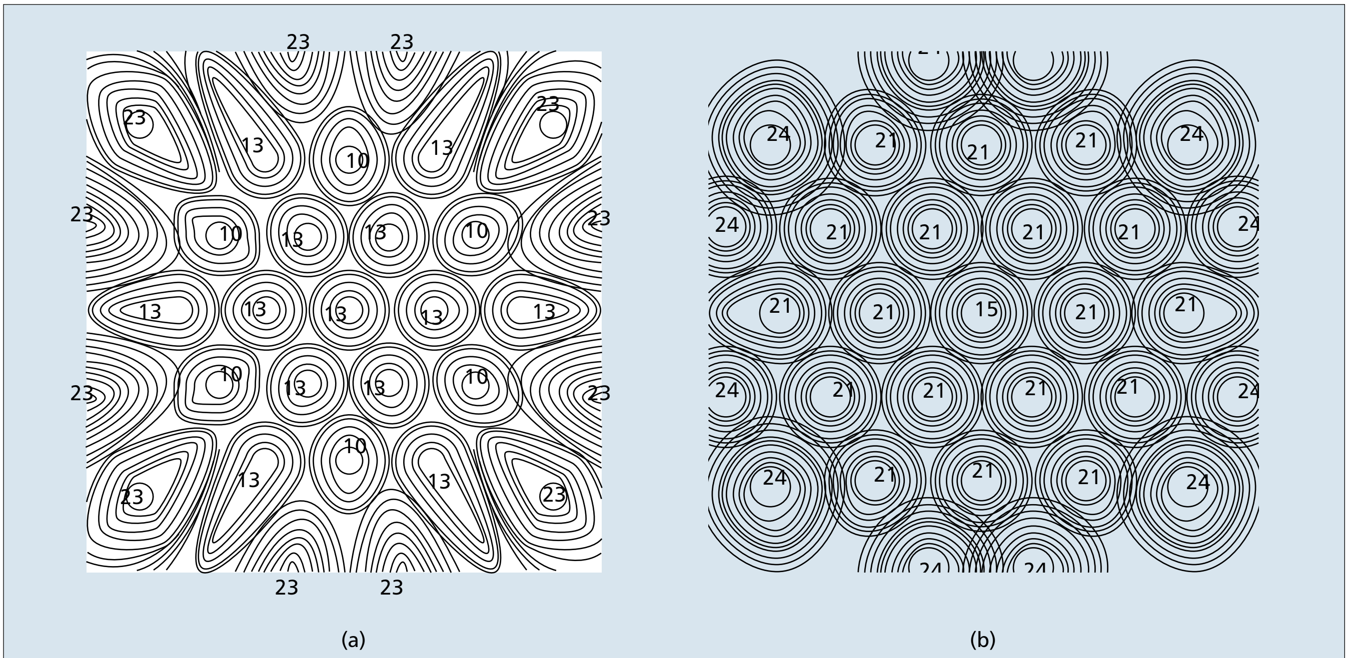


Figure 37. *Prototypes of multibeam antennas: a) MBH antenna (R_x) (seven elements, 47/48 GHz band); b) DBF antenna (R_x) (16 elements, 28/31 GHz band). (This photo appeared in [8].)*



■ **Figure 38.** *CIR contours for one channel of four: a) circular beams; b) optimized elliptic beams. (This figure appeared in [40].)*

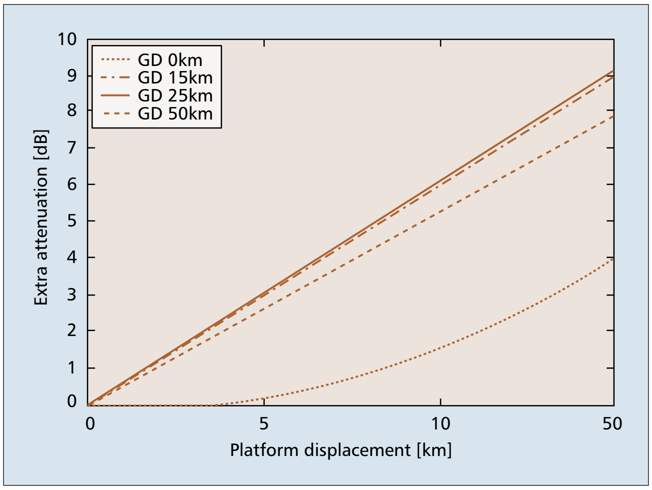
In the DBF antenna [3, 8, 46], a beam is formed by a combination of the array antenna and spatial digital signal processing. It is an "intelligent" next-generation antenna, referred to as a "*smart antenna*" or a "*software antenna*." The antenna supports automatic acquisition, tracking, interference separation, and so on by performing spatial parallel processing of signals received from the ground-user stations, thereby forming an antenna pattern. Since there is no mechanical drive component, this antenna is considered to be suitable for multi-element, large-scale, multibeam formations. This antenna is flexible, accurately steerable, accommodates a number of ground-user stations, provides a maximum gain continuously to a specific user, supports efficient frequency reuse performance by space-division multiple access (SDMA), removes undesired incoming interfering waves, reduces the interference to other systems (such as satellite systems), and also can estimate the Direction of Arrival (DOA) of authorized or unauthorized electromagnetic waves. Furthermore, since there are not mechanical components in such an antenna, the only problem with respect to the operation of a DBF antenna in the stratosphere is to find a way to cool it. Finally, it is considered to be robust against failure of a few components in the array antenna, while a high-speed calibration technique of the transmitting-receiving array antenna is possible via signal processing. However, remaining challenges are the improvement in the processing speed, the problem of heat-dissipation, and the improvement in gain and axial ratio for cases of large scan angles.

In [47, 48] the requirements of an on-board antenna suitable for the use of a HAP as a GSM base station were studied. A "smart antenna" was considered, which can estimate the position of the user, and modify and steer the radiation pattern of the antenna toward the location of the user. It is comprised of two basic function elements. The first is the Direction of Arrival estimator, while the second is the actual beam steerer. After this general structure, different software/hardware implementation configurations are possible. One approach, called switching beam, consists of a multibeam antenna with high directivity beams. A particular beam is switched on when a user is located within the beam footprint. Another approach includes a digital processor (the beamformer) jointly with the antenna array. The beamforming technique does not actually modify the radiation pattern of the array, but operates at the software level, implementing a digital spatial filter. The hardware complexity is lower in the case of the beamformer. Hence, a beamformer smart antenna is more suitable for a HAP. Some general considerations for designing a smart antenna suitable for HAP-GSM systems were given in [48]. In [47] the average error in both azimuth and elevation angles estimation was evaluated and compared to the main beam width.

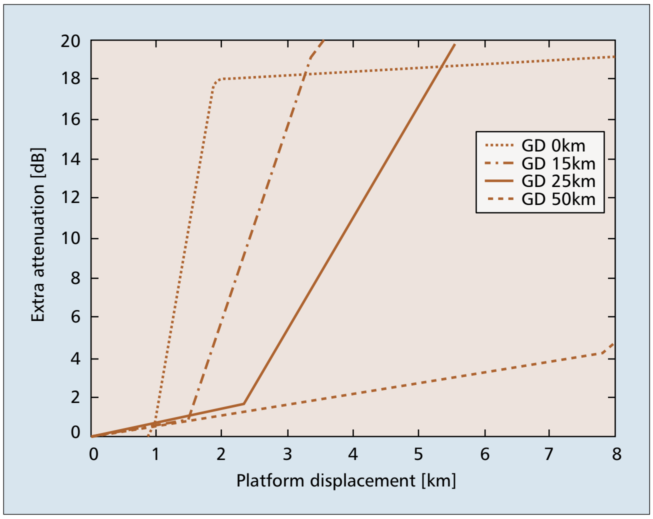
For ground terminals, highly directive antennas are required for high data rate applications. When the terminal is on a moving vehicle, then it should have a steering capability. Conceptually, the simplest solution is mechanically steered antennas, which provide good performance at low cost. However, high-speed steering may become problematic due to the large mass of such an antenna. DBF antennas can achieve rapid scanning, but this advantage is nullified by the cost associated with the very large number of antenna active elements that is required to achieve a high gain aperture. In the framework of the CAPANINA project, ongoing work is concentrated on the development and assessment of hemispherical lens antennas. Hemispherical lens antennas offer several advantages: only the feed, which has much less mass than the lens, has to be steered; multiple feeds can be employed for multiple beams; and there is no scan loss. Although there exist some disadvantages that are associated with any mechanically steered solution, these are ameliorated by the light weight of the feed.

In [18] a terminal antenna for the HALO Network was presented. A small dual-feed antenna was used with a millimeter wavelength (MMW) transmitter and receiver mounted on it. An antenna tracking unit used a pilot tone transmitted from the HALO aircraft to point its antenna at the airplane. Steerable antennas were deemed necessary for the HALO network due to the plane's motion.

As far as the Heliplat on-board antenna is concerned, active steering arrays were rejected due to power limitations, and aperture-type antennas were preferred [13]. The size of



■ **Figure 39.** *Power margin required to overcome the effects of worst case platform displacement with steerable fixed station antennas for different ground distances and a rainfall rate of 28 mm/h. (This figure appeared in [6].)*



■ **Figure 40.** *Power margin required to overcome the effects of worst case platform displacement with fixed FS antennas (5° beamwidth) for different ground distances and a rainfall rate of 28 mm/h. (This figure appeared in [6].)*

cells determines the required aperture size. For a service area of 60 km diameter and for an aperture of about 1 m^2, the number of on-board antennas at 28 GHz is around 120. The suitable antenna types for the Heliplat payload were mentioned in [7]. Corrugated horn antennas were said to be suitable for projecting the near-to-center cells. Lens antennas were considered for the other cells. Besides lens antennas, an offset-fed reflector was said to represent a good candidate for the outermost cells.

In [40] elliptic beams were proposed to maximize power at cell edges. Elliptic beams have been shown to offer advantages in terms of optimized power at cell edges, which is of utmost importance where RF link budgets are marginal. Figure 38 presents a study of CIR coverage areas for circular and elliptic beams. The proposed method provides uniform power distribution across the service area, which in turn allows the same Customer Premises Equipment (CPE) and other hardware to be used. In addition, extra capacity may be achieved through polarization diversity. Although circular horn technology is well established, elliptic beam antennas may require development.

The worst case displacement of the platform was addressed in [6, 49]. In [6] it was shown that this variation can be kept within typically 5 dB by providing steerable antennas, at both base and fixed stations. Figure 39 and Fig. 40 present the power margin required to overcome the effects of worst case platform displacement for different ground distances and for a rainfall rate of 28 mm/h, for steerable and fixed station antennas, respectively. In [49] the impact of airship location variations on the performance of the system was examined. The degradation in the earth station's Equivalent Isotropic Radiated Power (EIRP) and the Gain to Noise Temperature (G/T) ratio were examined for two types of antennas, a patch array and a circular aperture antenna. It was shown that only for low-gain antennas the variation of EIRP and G/T has a negligible value compared to other link parameter variations. It is worth mentioning that currently in the framework of the CAPANINA project, methods for steering an array of aperture antennas are being examined in order to counteract the movement of the platform.

Studies [50, 51] focused on the impact of the amplitude and phase errors on the sidelobe level of the on-board antenna which should be fairly low in IMT-2000 systems. An algorithm for simulating the statistical sidelobe level for a HAP antenna was presented, and simulation results showed that strict requirements on the sidelobe level can be met if the amplitude and phase errors are minor, a condition that can be achieved only by using digital beamforming. In [51] the design and fabrication of a simplified experimental model with four channel receivers and four linearly array cross dipole antennas for HAPs was presented and verified for operation in the S Band.

An interesting study of the antenna type that is suitable for solar-powered vehicles, namely power-limited vehicles, was given in [52] . In particular, a modulated retro-directive transponder was presented which reflects energy back in the direction of the interrogating signal. The geometry is illustrated in Fig. 41. Also, four ways to increase the link budget were presented.

Resource Management

Resource Allocation

Resource allocation represents an issue of paramount importance for any communication system. As far as HAP systems are concerned, few studies in the literature [53, 54] have treated this issue. FCA and DCA techniques have been developed and compared. In [53] a dynamic resource assignment scheme was proposed based on genetic algorithms with improved convergence performance. Channel assignment techniques for a HAP spot beam architecture were presented in study [54] for equal size, identical circular cells. A power roll-off approximation was developed to aid simulation and modeling of the schemes, assuming a base station at the center of each cell for a cluster of three, four, and seven cells.

In the framework of the HeliNet project, resource allocation strategies were developed for both packet-based communications and connection-oriented traffic, based on the TDMA frame of the IEEE 802.16 standard. Three channel selection schemes based on interference predictions were examined for packet-based communications. The performance evaluation of these schemes can be found in [7]. Concerning connection-oriented resource allocation, strategies that exploit the overlapping area between contiguous cells were also assessed [7].

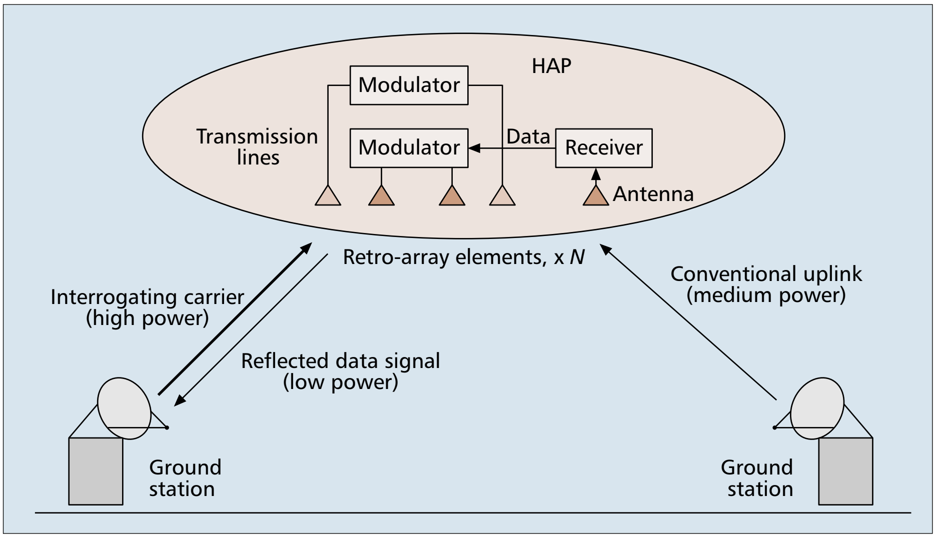


Figure 41. *A modulated retro-directive passive transponder placed on a HAP and illuminated by a ground station. (This figure appeared in [52].)*

Call Admission Control

A downlink Call Admission Control (CAC) scheme for a UMTS HAP station was presented in [55]. The potential movement of the HAP was compensated by appropriate station-keeping mechanisms or electronic beam steering. In CDMA systems CAC algorithms regulate the total number of mobiles in the service area in order to guarantee that all mobiles meet their respective QoS requirements, namely that the SIR is above a predefined level. An incoming call will increase the interfering level, so the forward link power transmitted to all mobiles must be increased to satisfy the SIR requirements. The interference geometry is shown in Fig. 42. In terrestrial systems, each base station has a fixed, maximum available downlink power. According to the scheme presented in [55], the call was accepted if a feasible power vector, that is, the downlink power transmitted to all mobiles, was found so as to satisfy the SIR requirements at available power levels. A unique feature of HAPs is that all transmitting beams originate from the same antenna on-board and it is easy to allocate the available power to the beams according to their demands. Blocking probability (P_b), call dropping probability (P_d), and grade of service (GoS = $P_b + 10P_d$) were used to evaluate the CAC schemes.

Two centralized CAC schemes were proposed in [56] for a HAP carrying a W-CDMA payload: one with priority queuing and the other with random service. Taking into account the reverse link interference for a mobile terminal, interference is created by the power received from other mobiles within its service area and from mobiles located at other cells. In order to assure that all the service classes maintain their respective QoS, a required SIR level should be satisfied. This imposes a constraint on the maximum total received power at an arbitrary base station. The schemes were evaluated in terms of P_b, P_d and GoS.

The literature lacks studies that examine Call Admission Control for integrated terrestrial-HAPs, HAPs-Satellite, or terrestrial-HAPs-Satellite architectures. 4G systems will comprise inter-working networks, and HAPs definitely constitute an attractive solution for the provision of broadband multimedia services. Considering that multi-mode terminals will be made available in the upcoming years, the development of innovative CAC schemes is deemed necessary: CAC schemes that will decide on the serving network according to the application and its QoS requirements, the traffic load of each candidate serving network, the pricing, etc. Moreover, in 4G networks a handover between different networks is required. A handover between different networks is usually referred to as a *vertical handover*. In this context, the development of seamless soft handover schemes is also crucial.

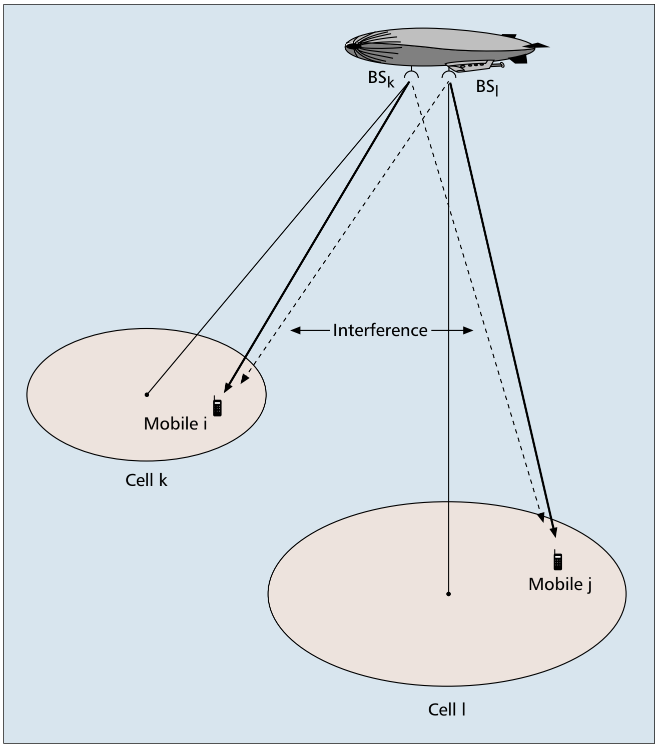


Figure 42. *HAP downlink interference geometry.*

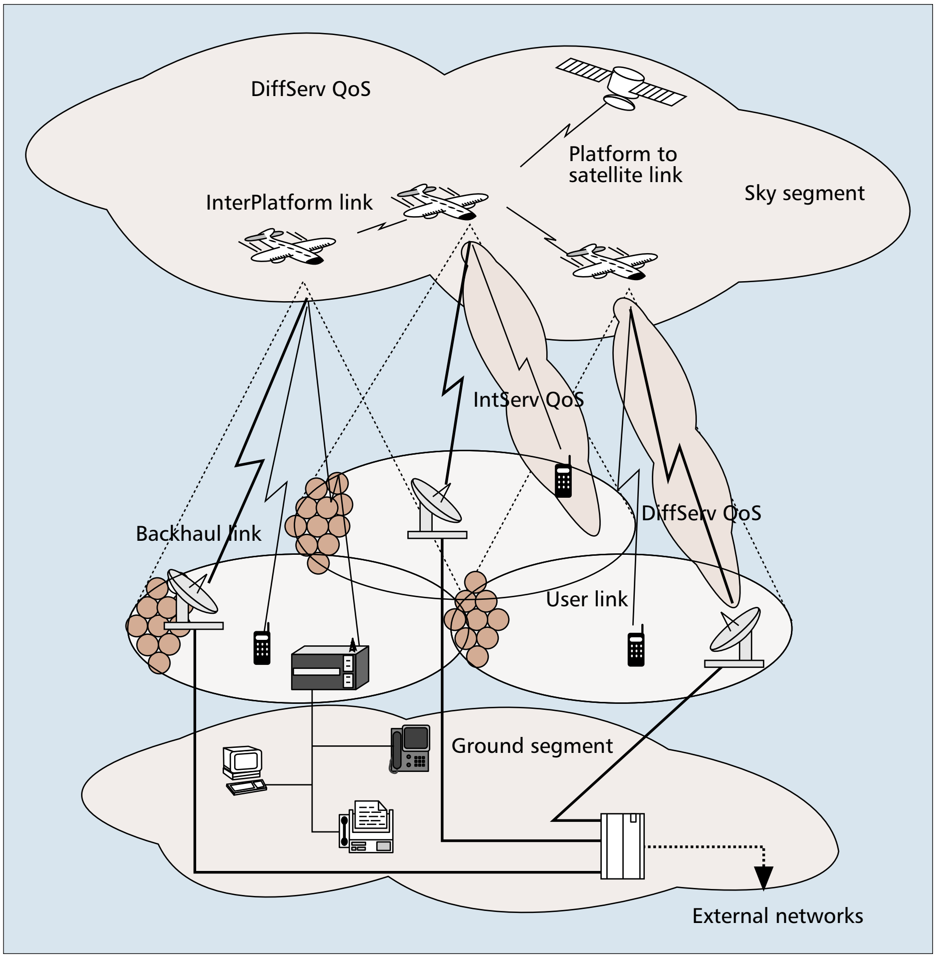
Medium Access Techniques

Resource allocation is directly connected to medium access techniques and network protocols in order to guarantee a high quality of service for multimedia traffic. For broadband wireless access (BWA) services it is likely that a modified version of the broadband standards IEEE 802.16/ETSI BRAN is applicable. Also, DVB (digital video broadcasting) and other satellite formats could be used. The choice of network protocols (such as TCP/IP, Wireless ATM, Wireless IP, and HIPERACCESS protocols) should be made on the basis of network topology (integration with terrestrial and satellite networks). Considering the movement of user terminals, or even the movement of the HAP, suitable handoff algorithms should be specified for different cell sizes and steerability of the on-board antenna array.

A novel Dynamic Broadband Multiple Access (DBMA) scheme is being developed at York University that is based on Packet Reservation Multiple Access (PRMA) schemes. This scheme is intended for use in both terrestrial and high altitude platform networks. The scheme is being designed for operation in the mm-wave bands (e.g. LMDS) for broadband multimedia services such as video-on-demand, high-speed file transfer, and Internet browsing. The access channel is split into several virtual regions (VRs), one for each service category.

Regarding PRMA, it would be very interesting to examine the performance of the CDMA/PRMA scheme, where several users can transmit in the same slot. Although such schemes have been proposed for terrestrial or LEO satellite systems, some of the features of HAP systems may result in an enhanced performance for this kind of multiple access technique. In particular, the other-cell interference is less in the case of HAP systems than in the case of terrestrial networks, and therefore more users can transmit in the same slot. Compared to LEO satellite systems, HAP systems present lower propagation delays, allowing users to contend again in the next slots owing to the low acknowledgment delay.

In [46] a new channel access technology for HAP communication networks, called Space Division Multiple Access (SDMA), was discussed. SDMA is a combination of TDMA, FDMA, and CDMA schemes with on-board multibeam antennas. According to that technique, the same channel, the same time slot, and the same code can be shared by different user terminals located at different areas, enhancing in that way the frequency reuse strategies. Uplink and downlink frames have the same duration, but uplink and downlink channels may have different bandwidths. There are two kinds of time slots, one for control information and one for transmitting data, with the length of the data slot being larger. Multimedia traffic can be supported due to the demand-based data slots assignment.



■ **Figure 43.** *The HeliNet network architecture.*

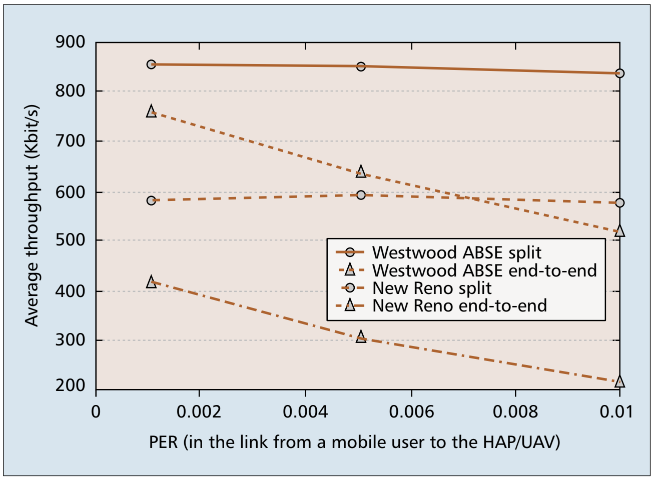
Networking Issues

Getting packets from the source all the way to the destination is an issue of utmost importance in all kinds of networks. Routing in IP-based hybrid systems is an issue that the designers of such systems must grapple with. The integration of a hybrid HAPs-Satellite system with IP/ATM networks was discussed in [15]. The general statement about optimal routes, regardless of network topology or traffic, is known as the optimality principle. One can state that many terrestrial routing algorithms have been based upon the concept of the shortest path between the source and the destination. However, IP routing can pose challenges over hybrid HAP-satellite systems. Topology information can rapidly become obsolete, especially when a LEO satellite system is employed to provide global connectivity. Nevertheless, many problems are simpler in HAPs systems owing to the low propagation delay and reduced delay jitter. In addition to other problems related to routing, end-to-end IP QoS has always been a challenging issue. Multi-Protocol Label Switching (MPLS) has been designed to enable IP routing based on hard performance guarantees and may facilitate seamless integration of terrestrial, HAPs, and satellite systems.

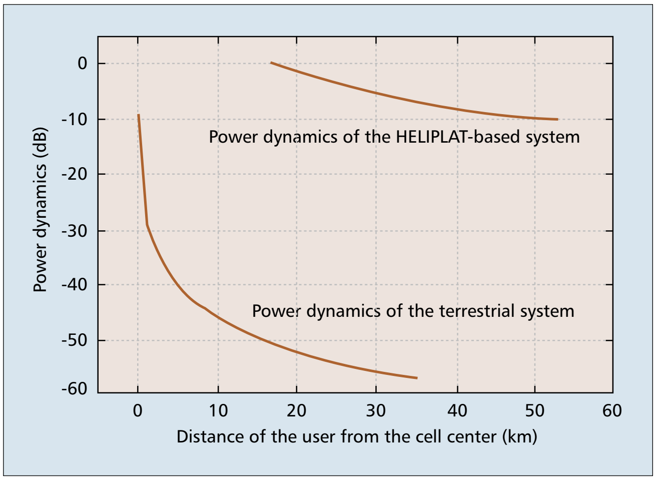
Multicasting is a compelling application that HAP systems are called to support. This can be supported via the widely used Internet Group Management Protocol (IGMP). The main challenge is to develop efficient multicast protocols for systems with changing rather than static links, which may be the case of HAP-satellite crosslinks.

An issue closely related to the MAC sublayer was addressed in [57]. This is the application of the IP protocol stuck over the HeliNet network, shown in Fig. 43. The existing IP QoS models, namely the Integrated Services model (IntServ model) and the Differentiated Services model (DiffServ model), were shortly described. The IntServ model seems more suitable because IntServ service classes can be easily mapped to MAC service categories. Mapping of QoS/CoS (class of service) parameters from network layer to radio interface can be performed through a suitable convergence sublayer. The IP convergence layer for HeliNet was presented. The radio interface of the broadband HeliNet system was assumed to be the IEEE 802.16 MAC service classes and these classes were shortly described. Simulation results proved that the introduction of such scheduling algorithms improve the ability of the radio interface to offer QoS/CoS to IP.

The main function of the network layer is to provide services to the transport layer at the network layer/transport layer interface. Regarding the transport layer, this is the heart of the whole protocol hierarchy. Its ultimate goal is to provide efficient, reliable, and cost-effective service to users. TCP



■ **Figure 44.** *Average throughput over a 230 sec transmission in the case of a mixed infrastructure comprising HAPs/UAVs and a GEO satellite. (This figure appeared in [58].)*



■ **Figure 45.** *Received power dynamics. (This figure appeared in [48].)*

(Transmission Control Protocol) was designed to provide a reliable end-to-end byte stream over an unreliable network. The study in [58] investigated the performance of TCP-based applications in a system comprising HAPs/UAVs and a GEO satellite. HAPs/UAVs can be employed to provide an emergency communication infrastructure when cellular base stations and Hot Spots are out of service due to natural hazards or terrorist attacks. Mobile users on the ground can use the HAPs/UAVs to communicate with each other and access the Internet via the satellite. Two different TCP protocols were assessed, namely TCP Westwood and TCP New Reno. Moreover, a PEP (performance enhancing proxy) scheme was proposed, according to which the TCP connection was split at the HAP/UAV. This intermediary performs processing on behalf of TCP endpoints to the greater benefit of performance. Figure 44 illustrates the average throughput for different combinations of transport protocols, utilization of the split mechanism, and various packet error losses (PER) in the link between the mobile user and the HAP/UAV. The combined use of TCP Westwood and the TCP split presented the best performance.

Applications and Related Projects

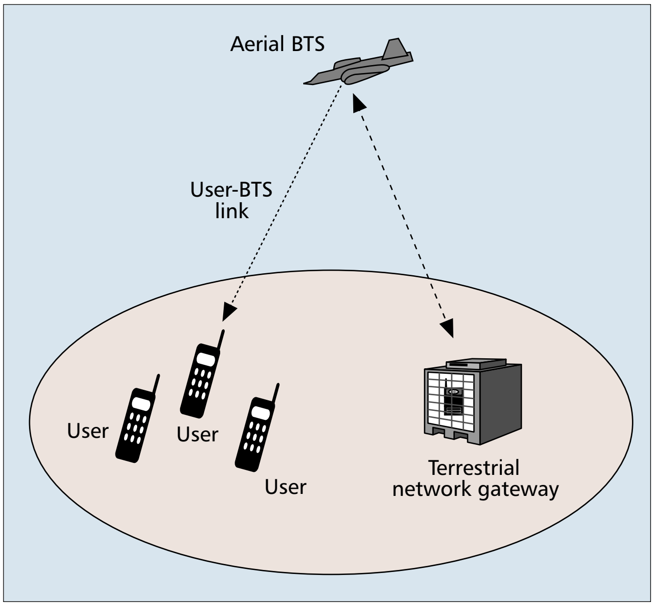
Applications

One of the attractive features of HAP systems is their rapid deployment time. If traffic volumes rise, this temporary network can be replaced by a terrestrial wireless or wired network. Furthermore, HAPs are very well suited to limited-scope applications. For example, they can be used to cover a seasonal or a one time event, e.g. the Olympic Games or a music concert. They can also be used for providing temporary services in disaster relief scenarios. For the bulk of emergency management applications, unmanned aircraft hold significant advantages over airships, mainly due to their immediate response time. Permanent communication applications that could be provided by HAPs are very wideband Internet access (e.g. 10 Mb/s in downlink and 2 Mb/s in uplink), entertainment video and audio, videoconferencing, cellular telephony [17, 48], broadband LMDS services, and access provision to digital networks (i.e. ISDN, Internet).

Different scenarios can be conceived as described in [17]. The first scenario employs the HAP as a "backup" base station covering a wide rural area, partially served by terrestrial base stations. The role of the HAP is to serve users in the regions not covered by the terrestrial network. The HAP in this case acts as an "umbrella." The second scenario considers the HAP providing a full-service coverage of a wide rural area, where no terrestrial network is active. In this case, the user density is much higher, imposing some technological complexity in terms of antenna technology and traffic management. HAPs can be easily integrated with the GSM standard, and their use as GSM base stations for low-user-density, impervious or sea regions, and for emergency applications was studied in [48]. Different solutions may be considered. The first is a base station completely on-board; the second is an on-board repeater using GSM frequencies on the link with the reference station, and the third is an on-board repeater using frequencies with the reference station not belonging to the GSM band. Regarding the first case, a radio link is needed to carry the traffic from the aerial platform to the base station controller (BSC) which connects the HAP with the ground network. This radio link can use GSM frequency bands or other bands. Considering power and weight constraints, a BTS (base transceiver station) redesigning is needed. The second and the third solutions reduce the hardware on-board equipment. If GSM frequency bands are used, then the spectral efficiency is reduced while the risk of interference increases. If higher frequency bands are used, smaller antennas are needed. Regarding the BTS, it can serve a limited number of users. In that article, it was shown that the use of the HeliPlat platform can be applied to GSM transmission without substantially modifying the standard. Figure 45 shows the attenuation curves of a terrestrial and an aerial system as a function of the distance between mobile terminals and cell centers. When considering UMTS transmission, full compatibility with the terrestrial standard seriously limits the system performance, and ad hoc strategies have to be adopted to design effective cellular stratospheric systems.

The flexibility of the system allows for utilization of HAPs not only for carrying telecommunication payloads but also for remote sensing: earth observation, satellite navigation applications, pollution monitoring, meteorological measurements, real-time monitoring of seismic or coastal regions and terrestrial structures, traffic monitoring and control, and agriculture support. With respect to remote sensing applications, images provided by HAPs are expected to be competitively priced, compared to equivalent images from satellites, due to lower infrastructure costs.

In [11, 12] the possible HAP applications were categorized as high power applications, typically provided from an airship, or as low power applications, provided from an unmanned solar-powered plane, and were considered to be niche market



■ **Figure 46.** *A terrestrial cellular network integrated with a cell by an aerial platform (macrocell). (This figure appeared in [59].)*

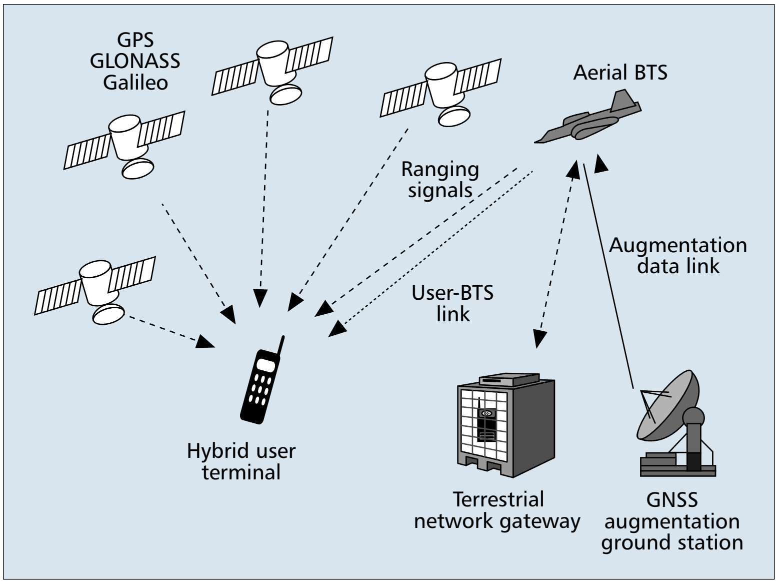
applications. 3G mobile services from HAPs will enable a rapid deployment. Over the longer term, HAPs can be used to cover regions with no substantial terrestrial infrastructure, or they can be used to cover areas subjected to short-term high traffic demands. HAPs are also suitable for developing countries where there is a lack of existing infrastructure and the growth in mobile phone ownership is rapid. Moreover, HAPs can be used to provide broadband wireless applications. The major competition is optical fiber. However, for regions with dispersed geography, such as the U.S. and the developing world, fiber may be less widely available. Regarding low power applications, HAPs may provide communications for primary businesses such as oil, gas and mining industries that often operate in remote regions, split across several sites. A backhaul link could be established via a local fiber backbone or via a satellite. The other low power applications are event or emergency servicing and the enhancement of communications in developing countries with poor infrastructure.

In [59] the role of HAPs for the provision of *navigation and positioning services* was studied. HAPs can have an active role in Global Navigation Satellite Systems (GNSS) as augmentation systems to GPS or Galileo, easily performing direction of arrival estimation thanks to their high position, collecting and broadcasting position information. But the real advantage of HAPs emerges from the fact that they can be used for providing both communication and navigation services, with mutual benefits for both systems, and they can be integrated with terrestrial networks (Fig. 46). By using HAPs it is possible to broadcast differential corrections evaluated by a terrestrial reference station. One useful technique for differential correction is to use a radio beacon able to transmit a satellite-like signal-in-space itself. For this reason, it can be considered a terrestrial satellite always in view and always available to the user, within a certain area. This system is defined as a satellite-like signal transmitter, typically called a pseudosatellite or pseudolite. In [60] a system that substitutes the terrestrial pseudosatellite with a pair of ground control stations with a controlled HAP was proposed. It was called *stratolite*. One constraint in the designing of such systems is that the position of the HAP should be finely controlled. Except for the accuracy, another benefit of hybrid positioning systems is that a smart user can select the optimal set of measurements according to the location. As for the integration of HAPs and satellites for both communications and navigation, the benefits can lead to cheaper enhanced solutions for infomobility applications. The navigation message can carry structured information, not only necessary for positioning, but also additional information on timing and availability of each navigation/communication satellite communication channel. A hybrid architecture is depicted in Fig. 47.

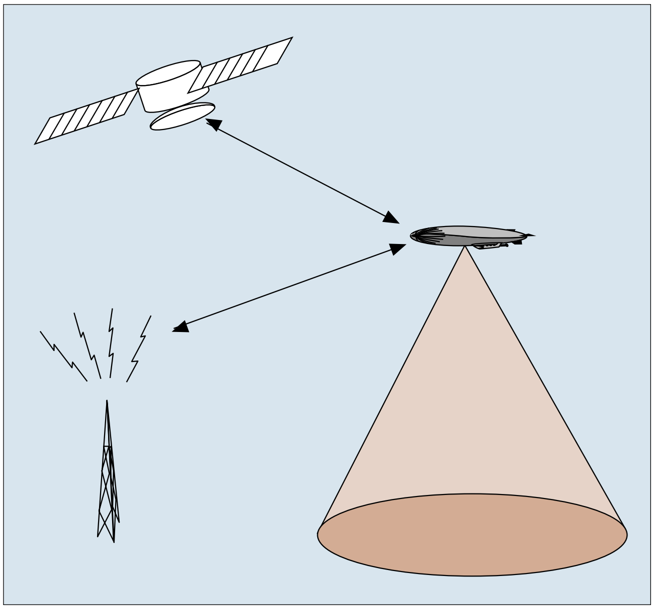
HAPs/UAVs can also be used for reconnaissance and surveillance missions, e.g. for transmission of video imagery through UAVs and satellites, demonstration of pre-strike targeting, and observation of the strikes for near-time bomb damage assessment (Fig. 48). A benefit of using HAPs for these applications is that they demand limited transmitting power from user terminals, and therefore this provides enhanced low probability of interception. Considering the huge size of airships, they might seem unsuitable for military purposes. However, their envelope is largely transparent to microwaves and they present an extremely low radar cross-section. The potential convergence of UAVs and HAPs for military communications was addressed in [61].

RELATED PROJECTS

Recently some projects focusing on aerial vehicles in the stratosphere have been funded. HeliNet was a project based upon high altitude very long endurance unmanned solar aerodynamic platforms, funded by the European Commission's 5th program. In the framework of the HeliNet project [62], a small prototype solar powered airframe was partially developed in conjunction with some key elements of power and propulsion systems. The prototype was based on the design of an unmanned solar-powered aircraft, named Heliplat. Heliplat was especially tailored for long endurance operations at an altitude of 17 km, supporting a payload of 100 kg and offering total available power for telecommunications applications of



■ **Figure 47.** *System architecture for provision of integrated services. (This figure appeared in [59].)*



■ **Figure 48.** *HAPs for military applications.*

800 W. Apart from the Heliplat, three prototype applications were examined as well, i.e. broadband telecommunication services, remote sensing, and navigation/localization. Among examples of broadband services that can be accommodated are broadcast TV, video-on-demand, Internet services and e-mail, LAN interconnection and Intranet, bulk file transfer, speech, and video conferencing. Environmental surveillance applications involve regional services for agriculture, hydrology, fire protection, flooding prevention, traffic monitoring and disaster relief support, pollution monitoring and meteorological measurement, real-time monitoring of seismic or coastal regions and terrestrial structures, etc. As for navigation services, the possibility of integrating HeliNet and GNSS2/Galileo to yield additional services was studied. Predictive maintenance of the railways is another case where HeliNet could play a significant role, either as a complement to the existing systems or as a stand-alone system.

After the successful completion of the HeliNet project, the interest in HAPs remained in the European Commission, and in November 2003 the EC started a new research project named CAPANINA [63], which is being partially funded by the 6th European Union's Framework initiative. Built on the HeliNet project, Capanina aims at the development of low-cost broadband technology from HAPs to deliver cost effective solutions to users in urban and remote rural areas, or to users traveling inside high-speed public transport vehicles (e.g. trains). In addition to the identification of appropriate applications and services and associated business models that will help to deliver "Broadband to All," the project intends to develop aerial links capable of delivering up to 120 Mb/s, a staggering connection 2000 times faster than today's dial-up connections and more than 200 times faster than a typical "wired" broadband facility. Users in rural and other impervious areas will benefit from the unique wide-area, high-capacity wireless coverage provided by HAPs. Additionally, use of "smart" roof-top antennas on trains will provide the moving user with high-speed Internet connectivity. Both mm-wave band and free-space optic communications technologies will be used. Free-space optic communications have the potential to deliver very high data rates in clear air conditions, and can be used for interplatform links and to supplement mm-wave band communications for backhaul traffic. In four years' time, the project hopes to see commercial services in operation from tethered balloons, although the high altitude platform side may take longer. Three trials are envisaged to take place. The first one started in the summer of 2004 in the UK, making use of a tethered balloon at an altitude of 300 m. The scope of this trial will be to demonstrate end-to-end network connectivity, broadband access up to 120 Mb/s to a fixed user through the 28 GHz band, the use of optical HAP-to-ground links, as well as to assess the use of tethered balloons to deliver "Broadband for All." The second trial, which will take place in Sweden, will use a free flying stratospheric balloon with the aim of assessing the atmospheric impacts on optical communications. The third trial, which is actually still under discussion, is likely to involve the use of a HAP in order to perform broadband trials.

Another HAP airship project is a Japanese national R&D project [3, 8, 46], also referred to as "SkyNet," commenced in 1998 and led by the Science and Technology Agency and the Ministry of Posts and Telecommunications. Further, the Communications Research Laboratory (CRL) and the Telecommunications Advancement Organization of Japan (TAO), which were merged into the National Institute of Information and Communications Technology (NICT) in 2004, are playing a central role in developing on-board equipment and ground equipment, focusing on the three fields of fixed communications, mobile communications, and broadcasting. This project aims at producing an integrated network of some 15 airships to serve most of Japan, providing interactive broadband communication services operating in the 28 GHz band, 3G communications, as well as broadcasting and emergency services. Perhaps this project represents the most comprehensive project on HAPs (spending is 100M€ to date). In the framework of this project, prototypes of "DBF" and "MBH" antennas were developed and demonstrated. Additionally, two prototype airships have been developed. The first airship, named "Ground-to-Stratosphere (GTS)," measures 47 m, has no propulsion system, and was successfully used to obtain thermal, buoyancy, and position control techniques through the ascent to the altitude of about 15 km and descent to a planned area in the ocean. The second airship, named "Low-Altitude Stationary (LAS)," measures 68 m and has a propulsion system. It will be used in order to obtain station-keeping mechanisms, as well as to evaluate control models obtained during the GTS flight. In June 2002, in collaboration with AeroVironment (a spin-off from NASA), its subsidiary SkyTower and NASA, the world's first digital high-definition television (HDTV) broadcast transmission from an altitude of 20 km was successfully tested. Pathfinder Plus, an unmanned, solar-powered aerial vehicle manufactured by AeroVironment, was used. This test was followed by an IMT-2000 (3G) mobile application that demonstrated video telephony using an off-the-shelf handset sold in Japan. In addition to this trial, another trial was planned for the last quarter of 2004, with the goal to demonstrate the use of optical links using the LAS prototype airship. Currently, basic technologies on solar cells and fuel cells are under development and are being evaluated.

A similar but much more modest project than "SkyNet" is underway in Korea, jointly managed by the Electronics and Telecommunications Research Institute (ETRI) and Korean Aerospace Research Institute (KARI). Although the project will initially work with a low altitude platform, an airship is planned for 2008. The platform will provide 3G services as well as services at 48/47 GHz.

ESA has recently set up some studies related to telecommunications from HAPs. Initially, the most promising stratospheric service candidates were selected as broadband connectivity, 3G base station service, and digital audio broadcasting (DAB)/DVB-T. Moreover, criteria for the selection of an appropriate platform were defined and a clear preference

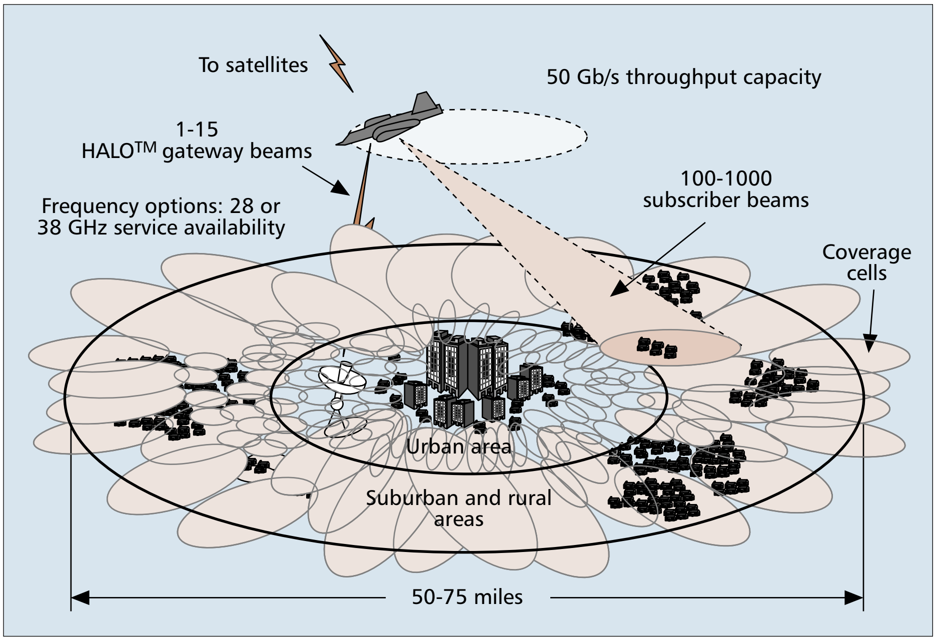


Figure 49. *The HALO network. (This figure appeared in [18].)*

was given to solar powered systems. A rough cost estimate was performed based on analogue experience for manned airships and manned airplanes which show a linear relation between platform life cycle costs and maximum take-off mass. The ongoing work now concentrates on the development of suitable telecommunication system architectures as well as the design of a possible European stratospheric platform.

In the U.S., significant interest has been drawn toward HAPs. Recently, the U.S. Missile Defense Agency (MDA) funded project, known as High Altitude Airship (HAA) Advanced Concept Technology Demonstration (ACTD), has been concentrating on the role of unmanned airships in Homeland security. Although the prototype airship will stay aloft for about one month, carrying a 1800 kg payload, future airships are expected to stay airborne for up to a year and carry a payload greater than 1800 kg. Initially, airships will give persistent wide-area surveillance against a full spectrum of air, land, and sea threats, while the next stage of this project will focus on the development of an airship that could be used in ballistic and cruise missile defense. It is envisioned that by the end of the decade there will 12 airships around the perimeter of the U.S.

Sanswire Technologies, Inc., a U.S. company, has entered into a joint venture with Telesphere Communications, Inc., to launch a series of high altitude airships called "Stratellites" in order to provide high-speed wireless Internet access to the entire continental United States and parts of Canada and Mexico. The airships will be held stationary in the stratosphere at an altitude of 21 km and will be remotely controlled from tracking stations on the ground. Each Stratellite is designed to stay aloft for up to 12 months, at which time it would be replaced by a duplicate Stratellite, allowing a seamless exchange that will prevent outages to subscribers.

The NASA ERAST program (Environmental Research Aircraft and Sensor Technology) covers several areas of research, and aims toward three types of long endurance platforms (Centurion, Alliance I, and Helios). Through funding support from NASA, AeroVironment has developed the unmanned solar-powered aircraft named Helios, which is capable of continuous flight for up to six months or more at altitudes greater than 60,000 ft. Helios will provide a Telecommunications platform from stratosphere, hence the name "SkyTower" that was given to the stratospheric communications platform. The stratospheric communication network will be comprised of airborne segments that will communicate with user terminals and gateway stations serving as an intermediate interface between the aircraft and the existing Internet and PSTN connecting systems.

SkyStation Inc. and the High Altitude Long Operation (HALO) Network project by Angel Technologies Inc. were two U.S. projects aiming to provide digital broadband telecommunication applications from stratospheric platforms. SkyStation proposed a network based on a lighter than air stratosphere airship. However, the constraints imposed by airships' drawbacks limited the evolution of this project. As far as the HALO network is concerned [18], the HALO-Proteus aircraft was specially developed a few years ago to operate as a solitary "hub" in a broadband wireless metropolitan network, capable of serving thousands of users on the ground. A fleet of three aircraft would have been cycling in shifts to achieve continuous service. The proposed system was manned in order to obtain Federal Aviation Administration (FAA) approval and used current technology, but the designers hoped that once the concept was proven the aircraft could be manned by a single pilot and then eventually be unmanned. However, little has been heard from this venture lately despite the fact that this network represented generally established technology. The proposed HALO network is illustrated in Fig. 49. The services to be delivered included T1 access, ISDN access, Web browsing, high-quality videoconferencing, large file transfers, and Ethernet LAN bridging.

Geoscan (UK) Plc is a British-Russian Technology Partnership that has been developing a network based on the Russian M-55 stratospheric aircraft. The Geoscan Network will provide broadband fixed wireless services, 3G and 4G services, and solutions for earth observation and natural disaster monitoring. With the flight time being four or five hours, four or five aircraft will be flying in turn in order to provide continuous service.

Advanced Technologies Group (ATG) of Bedford, U.K. wishes to develop a range of airships. ATG, at one time in collaboration with SkyStation International of the U.S., proposed an airship named StratSat, 200 m in length, supporting a communications payload of up to 800 kg. Lindstrand Balloons, another U.K. company, has also proposed HAP airships. A novel design of HAP comprising several smaller airships joined together in an "airworm" configuration has been developed by the University of Stuttgart. This sausage-like formation aims to provide the lift while avoiding some of the structural and aerodynamic problems associated with very large airships. As far as unmanned aerial vehicles are concerned, General Atomics is a U.S. (San Diego) based manufacturer of UAVs , while the Global Hawk project of the Defense Advanced Research Projects Agency (DARPA) is concentrated on the use of UAVs for military applications, such as reconnaissance.

While HAPs have many appealing features, their technology is still immature. From this perspective, tethered aerostats constitute an attractive alternative for the provision of broadband services. They may operate at an altitude of 5000 m or more, although there are evident implications for air traffic safety and their use is highly restricted, with the majority operating at much lower altitudes. Platform Wireless International Corporation developed an Airborne Relay Communications system ("ARC System") which was successfully demonstrated in March 2001. This system uses a 150-ft long tethered aerostat at 15,000 ft. and is able to provide wireless communication services similar to those offered by current terrestrial cellular systems. In March 2004 the Platform Wireless International Corporation was awarded a contract for the design of an ARC System-based national telecommunications network for a prominent corporate conglomerate in South Asia. Similar to Platform Wireless International Corporation, SkyLINC Ltd. is an innovative company that is developing its own system, named LIBRA, for the delivery of broadband services from a tethered balloon. With the ability to offer expandable, 2 Mb/s symmetric links to a coverage area of up to 5000 km^2, LIBRA represents a cost-effective alternative to existing terrestrial masts. Another major application of tethered aerostats is surveillance. Large numbers are deployed along the U.S.-Mexican border to detect unauthorized crossings, while aerostats are currently deployed by the DoD and by the U.S. for military purposes, as part of the "Homeland Security" initiative.

FUTURE PERSPECTIVES

A raft of technologies is currently in use and under development in order to satisfy the growing demand for high data rate communications. Among them, Digital Subscriber Line (xDSL), 2.5G and 3G networks, WLANs, and satellites have been widely used for the provision of communication services. However, it has always been a dream of communications engineers to develop a wireless system that, while covering a wide area, would provide broadband services with low propagation delay. With some of their outstanding characteristics, as well as their capability to provide a variety of services beyond just telecommunications, HAPs seem to represent a dream come true for those communications engineers working on the "ideal wireless system." While possessing many of the advantages of terrestrial and satellite systems and having the potential to provide broadband communications in a cost effective way, HAPs do not intend to replace existing technologies, but rather complement them. Moreover, HAPs have the potential to deliver a wide spectrum of services and applications. Except for broadband services, they have the potential to deliver 3G-based communications, remote sensing, and navigation applications, while they are also particularly suited to disaster relief applications. It is envisaged that a HAP will be capable of providing a compelling range of these services and applications, presenting a profitable case in this way. However, HAPs are at a similar stage of development as communications satellites were in the 1960s, and only recently, some substantive projects have commenced. Hopefully, in the next few years some of these projects will come to fruition, confirming the usefulness of HAPs, and populating the skies with the first networks of this kind.

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