

# **Part One**

## **Basics, Enabling Technologies and Economics**

COPYRIGHTED MATERIAL



# 1

## Introduction

### 1.1 Introduction

With an ever increasing demand for capacity for future generation multimedia applications, service providers are looking for novel ways to deliver wireless communications services. In developed countries we are familiar today with seeing mobile phone masts dotted around the countryside, but these can be expensive to deploy and continually service. This patchwork of coverage delivers cellular communications, an efficient way of delivering high-capacity density services. We use the term cellular here to describe the way in which the radio spectrum is reused in order to deliver the high-capacity densities. This concept is now being adopted with a number of technologies, including the widely known 2G and 3G mobile systems, but also new technologies such as WiMAX, and also WiFi, where in this latter case islands of coverage (hot-spots) are provided through spectrum reuse.

An alternative for more rural or less developed areas is to use satellite communications. Satellites today are increasingly sophisticated, and capable of delivering spot beam coverage, with minimal ground infrastructure. However, they are incapable of matching the high-capacity densities seen with terrestrial infrastructure.

A possible third alternative way of delivering communications and other services is to use high altitude platforms (HAPs). HAPs are either airships or planes, which operate in the stratosphere, 17–22 km above the ground [1, 2]. Such platforms will have a rapid roll-out capability and the ability to serve a large number of users, using considerably less communications infrastructure than required by a terrestrial network [3]. Thus, the nearness of HAPs to the ground, while still maintaining wide area coverage, means that they exhibit the best features of terrestrial and satellite communications. We will explore these benefits in more detail in later sections of the book.

The main goal of HAPs is to provide semi-permanent high data rate, high capacity-density communications provision over a wide coverage area, ideally from a fixed point in the sky. In practice due to aeronautical constraints all HAPs present compromises. It is helpful to specify the following HAP ‘vital’ statistics, and as we shall see, these may radically affect the communications system design and ultimate capabilities:

- payload power, mass and volume;
- station keeping and attitude control;
- endurance.

HAPs can be divided into four categories (as shown in Figure 1.1):

1. Manned plane, e.g. Grob G520 Egrett [4, 5].
2. Unmanned plane (fuel), e.g. AV Global Observer [6].
3. Unmanned plane (solar), e.g. AV/NASA Pathfinder Plus [7].
4. Unmanned airship (solar), e.g. Lockheed Martin HAA [8, 9].



Manned Planes  
–e.g. Grob G520T Egrett  
(a)



Unmanned Hydrogen Powered Planes  
– e.g. Global Observer  
(b)



Unmanned Solar Powered Planes  
–e.g. NASA/AV Pathfinder Plus  
(c)



Unmanned Solar Powered Airships  
–e.g. Lockheed Martin HAA  
(d)

**Figure 1.1** Examples of the main types of high altitude platforms: (a) manned plane. Reproduced by permission of © Grob Aircraft AG; (b) unmanned plane (fuel). Reproduced courtesy of AeroVironment Inc. [www.avinc.com](http://www.avinc.com); (c) unmanned plane (solar); Reproduced from NASA - <http://www.dfrc.nasa.gov/gallery/photo/index.html>; (d) unmanned airship (solar). Reproduced by permission of @Lockheed Martin

To date only the first type of HAP is available for commercial use, although HAPs in categories 2 and 3 have been tested experimentally. The fourth category, the unmanned solar powered airship, still has to be realised.

The HAP most suited to the general communications requirements is the unmanned solar powered airship, in view of its on-station lifetime performance and payload capabilities. However, this type of platform is also the most ambitious, as new materials and designs need to be developed and airship handling techniques re-learned. In the short and medium terms it will be possible to make use of existing or other HAPs in the development phase, e.g. the manned and unmanned planes. All of these have more limited capabilities, but can still be used for missions with more limited requirements. It is also possible through careful system design to ameliorate the effects of some of these constraints as will be discussed later. It is also worth noting the intersection between HAPs and more widely known unmanned aerial vehicles (UAVs), which tend to fly at lower altitudes (with the possible exception of Global Hawk [10]). More information on UAV technologies can be found in [11].

Given the state of maturity of the different HAP vehicles, a step-by-step development approach is now being pursued by organisations, with the aim of generating confidence, develop the technology, and perhaps more importantly provide revenue streams for manufacturers. We will describe some of the projects underway later in Section 1.5. Thus an investment–confidence cycle can be created. Designing payloads, and describing payload characteristics in a modular way, will make them suitable (ideally) for all platform types, reinforcing a commonality of requirements and specifications, and thereby making the technology more accessible to non-specialists [12]. We expect that one or more platform modules will be incrementally deployed to serve a common coverage area, with each platform serving one or more payload modules (telecom or other). Such platforms will be networked, with the detailed operations transparent to the end user.

To aid the eventual deployment of HAPs the ITU has allocated spectrum around 48 GHz worldwide [13] and 31/28 GHz for selected countries [14], with spectrum in the 3G bands also allocated for use with HAPs [15]. There is now an emerging body of work on communications delivery from HAPs both for eventual 3G deployments, e.g. [16–18], as well as for communications deployed in the mm-wave bands. Spectrum sharing studies have been carried out, e.g. [19], since all of these bands will be used by, or adjacent to, other services.

To deliver the best-of-both-worlds of satellite and terrestrial communications systems, efficient spectrum reuse will be required to ensure that such deployments can deliver high spectral efficiencies. We will explore specific cellular techniques and reuse solutions in detail in later chapters, but fundamental to the delivery of cells on the ground is the use of spot-beam antennas on the HAP. One issue not really

in common with the terrestrial and satellite counterparts is the relatively poor station-keeping that these HAPs will exhibit. This requires careful design of both the HAP and potentially user terminal equipment, to ensure that the antennas are able to stay pointing continually in the right direction in order to maintain the communications links. One alternative way of coping with such movements is to handoff users from one cell to another, but unlike terrestrial handoff, here it is the cells that move and not necessarily the users.

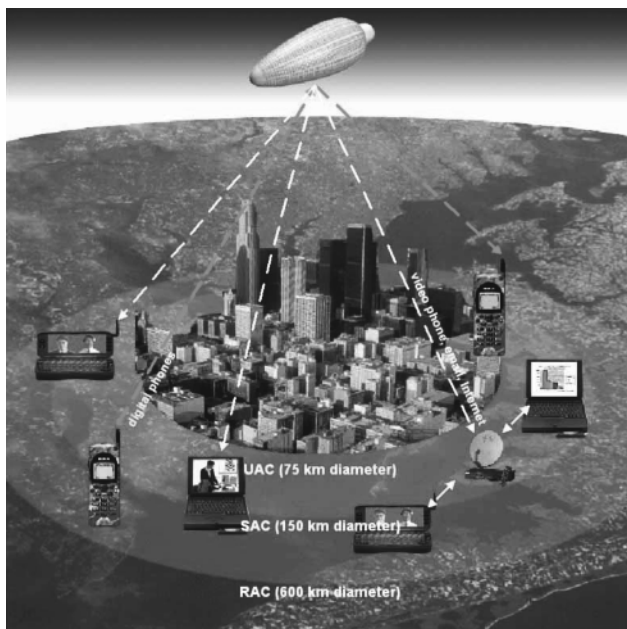
One big advantage for HAPs over terrestrial systems is that cells can be regularly spaced over an area, so that coverage is substantially unaffected by geography and terrain, and since they all originate from the same HAP this centralisation can be additionally exploited to improve resource utilisation.

The purpose of this book is to focus on how HAPs can be used to deliver broadband communication services over a wide coverage area, typically 60 km wide, based on terrestrial standards. Much of the work is loosely based on the use of the broadband WiMAX standard and exploits the mm-wave bands, e.g. 31/28 GHz, given the bands already approved for HAPs by regulators. However, many of the techniques and principles can be applied more widely, even to lower frequency broadband communications (2–5 GHz) as well as HAP delivery of more conventional 3G mobile services. We have chosen a target data rate of 120 Mbits/s per cell to carry out much of the analyses, which is a fundamental limit constrained by the link budget (e.g. limited by the antenna sizes and transmit powers chosen). This is currently greater than most terrestrial WiMAX systems will support on a per sector basis, but the aim here is to be more technology neutral, hence providing a degree of future proofing.

## 1.2 History

Like with the start of many new fundamental technologies it is very difficult to pinpoint the inventor or the first time it appeared in print. HAPs have their origins back to 1783 when the Mongolfier brothers launched the first hot air balloon. However, it is not until the early 1960s that we start to find direct references or use of airborne craft capable of providing a semi-permanent presence to deliver communications. One example was Echo which was a balloon that was used to bounce radio signals from the Bell Laboratories facility at Crawford Hill to long distance telephone call users [1]. At a similar time the Communications Research Laboratory of Japan published a study on the use of airships to deliver communications. To our knowledge these were not taken much further, and there are other anecdotal references to projects over the years since then. The next public reference that we have come across appears in an editorial in 1992 [20], again proposing a similar concept.

It was 1997/8 when HAPs really started generating interest. This was catalysed by SkyStation International who put forward the concept of a 200 m long solar powered airship HAP, capable of flying at 20 km altitude for a period of years. Their aim was to provide 3G and broadband communications, both in their infancy at that time. Coverage was planned to be upwards of 300 km diameter, as shown in Figure 1.2, delivered from 700 cells produced from a phased array antenna system. They had a number of credible backers including Alexander Haig former US Secretary of State, and Y.C. Lee as its Chief Technology Officer. This project was taken seriously and much of the initial work within the International Telecommunications Union – Radiocommunication Sector (ITU-R) was undertaken on behalf of SkyStation, with ITU-R Recommendation F.1500 based on their design. They successfully managed to get 47/48 GHz band for HAPs use at the World Radiocommunication Conference (WRC) in 1997, with further frequencies at subsequent WRC gatherings.



**Figure 1.2** The original SkyStation HAP broadband and 3G communications concept. Reproduced from © SkyStation

At a similar period of time, as a result of this spurt of activity, other projects commenced. Another major project was put forward by Angel Technologies [21] based on a manned stratospheric plane, the Proteus, and developed by Scaled

Composites. A photograph of their plane is shown in Figure 1.3, complete with antenna pod beneath the main fuselage. They planned to deliver high capacity communications services over areas of high population, again similar to SkyStation.



**Figure 1.3** The Angel Technologies – HALO plane with antenna pod below. Reproduced from © Angel Technologies

Both of these projects failed. The SkyStation concept was ahead of the technology, especially the airship technology, of the time. Angel Technologies aircraft technology was more conventional, but the communications technology and capability claims were over ambitious, resulting in a failure of the business model. Both the technology and business model design are discussed in later chapters.

In Asia at the same time, both Japan and Korea decided to start up their own projects.

Japan put significant funding into their activities through a millennium project initiative that commenced in 1998, with the primary splits being between aeronautics, telecommunications, and earth observation. The Japan Aerospace Exploration Agency (JAXA) coordinated the aeronautics aspects, with the telecommunications activities under the coordination of the National Institute of Information and Communications Technology (NICT). The project and its accomplishments are described in Section 1.5.6, but the aim was to again develop a 200 m long solar powered airship, capable of delivering telecommunications and remote sensing.

Similarly, a smaller project was started by the Korean Government, split across aeronautics and telecommunications, run by the Korean Aerospace Research Institute (KARI) and Electronics and Telecommunications Research Institute (ETRI).

Activities in Europe took longer. The European Space Agency undertook an initial study on high altitude long endurance (HALE) [22], but did not put significant



investment in a full scale project. They later commissioned a second study a number of years later [23], but still remain cool to the concept. In 1999 Professor Bernd Kröplin of the University of Stuttgart and Per Lindstrand of Lindstrand Technologies [24] shared the Körber Prize [25] for innovation for putting forward the outline aeronautical designs for an unmanned solar powered airship. The prize provided only modest funding, and insufficient external backing meant a full scale airship was never achieved.

In 1999/2000 a Consortium, coordinated by Politecnico di Torino, Italy, was awarded the 3-year long HeliNet project [26, 27], funded under the 5th Framework Programme of the European Community, and which kick-started the authors' activities in the field. This project was to develop a scale-sized prototype solar powered plane and three pilot applications: broadband communications; remote sensing; and traffic localisation. This was followed 3 years later by the CAPANINA project [28, 29], funded under the 6th Framework Programme, and coordinated by the University of York, UK. This aimed to capitalise on HeliNet, but now in the more focused area of HAP delivery of broadband communications for fixed and high-speed users (and also the main focus of this book). Again more details are discussed in Section 1.5.3.

In the USA over this same period there were a number of other activities, led by NASA and latterly AV Inc [30]. NASA's ERAST programme had already successfully developed the Pathfinder, Pathfinder Plus and Helios unmanned stratospheric planes, each capable of flying modest payloads. NICT of Japan saw this potential, and given that JAXA's airship programme was running more slowly than the NICT communications programme, they decided to undertake pioneering telecoms trials with Pathfinder Plus in 2001. In Hawaii, they successfully demonstrated 3G and HDTV. Helios, NASA's most futuristic stratospheric craft, suffered a mishap in 2003 [31], and crashed in the Pacific Ocean while testing a regenerative fuel cell design, which prevented NASA and NICT carrying out a further round of stratospheric tests.

Following the Helios mishap, AV Inc (a NASA spin-off) started developing the Global Observer, with a 1/5 scaled prototype flying in 2005. This was successfully used at the end of 2006 for a NASA/NICT/CAPANINA joint test in California.

Lockheed Martin [8, 9, 32] in the mean time had also received US Defense Department funding to develop an airship HAP for the military. To the authors' knowledge this activity is still underway.

As of 2008 there are still a number of activities ongoing, each building on previous developments. One of the most significant is the StratXX [33] project in Switzerland that is developing a solar-powered airship HAP. Key personnel worked on both the HeliNet and CAPANINA projects. There are activities underway with manned stratospheric aircraft, e.g. ERS srl [34] in Italy, using the Grob family of planes. There is also COST 297–HAPCOS scientific cooperation action [35], which was an

international discussion forum on HAPs for Communications and Other Services which brings together radio and optical communications, and aeronautical experts on a bi-annual basis. Experts are based in 20 signatory countries, with meetings typically hosting 50–60 delegates. Regulatory activities at ITU-R still continue with much of the work set on studying the multiple system sharing in bands around 5–7 GHz.

### 1.3 Wireless Communications in a HAP Environment

With the HAP characteristics in mind that we discussed earlier, this section describes in more detail the general concepts and system level design issues relating to the use of HAP(s) to deliver segments of a broadband communications system. HAPs are ideally placed to deliver ‘first/last mile’ and ‘second’ mile segments (referred to later as fronthaul), interfacing to more conventional terrestrial and satellite segments via backhaul link(s) structure.

There are a number of interlinked system design issues, ultimately constrained by the platform characteristics.

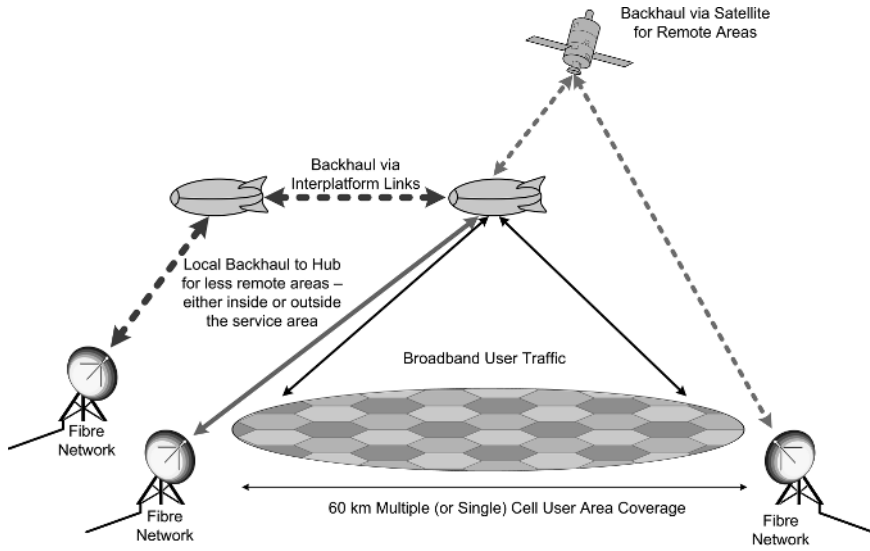
#### 1.3.1 *Comparison of HAPs Capabilities when Compared with Terrestrial and Satellite Systems*

The fundamental point is that HAPs can and should exploit the advantages of both terrestrial and satellite systems. Owing to the similar link lengths, maximum link data rates can be comparable with terrestrial wireless links. Fundamentally HAPs can provide regional coverage – a much wider coverage area than a terrestrial base station – owing to the high look angle reducing the attenuation caused by terrain and buildings, etc. Compared with geostationary satellites there is a fundamental path loss advantage of up to 69 dB, enabling HAPs to offer higher data rates and/or use smaller antennas. Thus, if the next generation of satellites deliver their promised link data rates in the hundreds of Mbps range, this HAP link budget advantage can always be exploited in the future to increase link data rates above that of corresponding satellites.

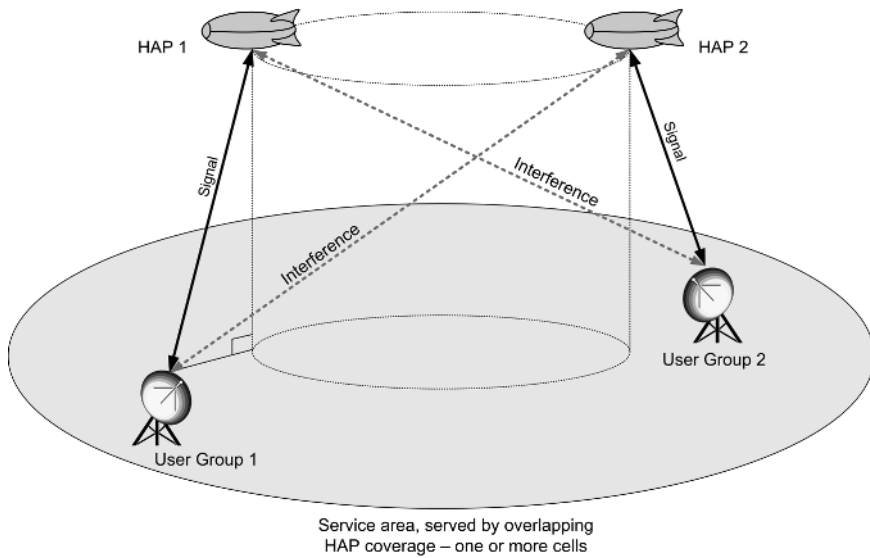
##### 1.3.1.1 Capacity and Coverage

The total capacity of a single HAP-based system is ultimately limited by the HAP and the size, weight and power that can be reserved for the payload. The size of the service area is constrained by the architectural and HAP payload configurations. Three main architectural configurations have been analysed in depth by researchers (these are also discussed in more detail in later chapters):

- **Cellular ubiquitous coverage over a service area** [see Figure 1.4(a)] [2]. The capacity is determined by the number of cells and data rate per cell, with



(a) Cellular architecture



(b) Multiple HAP constellation (overlapping coverage)

**Figure 1.4** HAP architecture examples

the cell size and number of cells controlling the size of the service area. The cell size is dominated by the beamwidth of the HAP antenna, and this beamwidth is ultimately controlled by elements of the link budget, including, path loss, ground terminal antenna gain and transmit power. Interference between co-channel HAP antenna beams is an important factor affecting the capacity (as does the number of beams on a specific spectrum assignment) [26].

- **Spot beam islands of coverage** [36]. This configuration is probably best suited for specialist broadband connections. HAP capacity is still constrained by the size of payload, and will be similar to the previous case, but now the size of the service area can be decoupled from the capacity constraints, subject to satisfying the link budget for any specific link. The maximum number of spot beams is again affected by the HAP payload capacity, and the interbeam interference caused by the HAP antenna power profiles. It has been shown that 1 Gbps per spotbeam is theoretically achievable in clear air [36] with steerable ground and HAP antennas compensating for HAP attitude movements.
- **Multiple HAP constellations to provide capacity enhancement** [see Figure 1.4(b)] [37]. Operating a constellation of multiple HAPs can increase capacity within a service area. Studies have shown that it is possible to support 16 HAPs on the same spectrum assignment by exploiting the directionality of the ground-based antennas to reduce the interference from other HAPs in the constellation. Such a strategy can be used in conjunction with both architectures above. Multiple HAPs can additionally be used in a coverage enhancement configuration by moving them further apart.

#### 1.3.1.2 HAP Fleet Management and Handoff

In the early days of HAPs, developers considered that long endurance was a fundamental requirement in order to provide long endurance missions, and an enhanced cost-benefit. However, today several companies/researchers have developed detailed fleet management schedules that would enable multiple short duration HAPs to provide a continuous presence over multiple service areas cost effectively [38]. Such concepts have been used for many years with military AWACS systems. However for continuous broadband delivery, fleet management must be accompanied by inter-HAP handoff strategies that are capable of switching over all the communications from one HAP to another without loss of service. This may require specific developments in the case of wireless broadband equipment, which is more accustomed to operation with fixed point-to-point terrestrial operations. In the case of more conventional user protocols, operating at lower data rates, such as WCDMA and WiMAX (IEEE802.16-2004), existing handoff strategies should suffice, even though they have been developed for a moving user and fixed base station configuration (here the HAP base station is moving).

Intra-HAP handoff can be used with the cellular architecture to switch traffic between spot beams to limit the need for payload stabilisation to compensate for HAP attitude movements, especially yaw (rotation). Compensation for pitch and roll (and drift) is still required, to keep the coverage over the service area, or alternatively the size of offered coverage must exceed the size of required service.

While the technical feasibility of all of the above has been assessed positively, practical trials relating to these above issues have yet to be carried out.

### 1.3.1.3 Radio Propagation Environment

The radio propagation environment is somewhat different from terrestrial (and to a lesser extent satellite) scenarios. The frequencies above 10 GHz will in general require line of sight paths and be increasingly prone to rain attenuation, but due to relatively high slant path angles, such attenuation is restricted to the first few kilometres of the link from the ground. Typical attenuation factors are 20–30 dB for 99.9% availability at 31/28 GHz and approximately 10 dB higher for 48/47 GHz [39, 40]. It is important that link budgets include suitable figures, and this attenuation can normally be compensated for through higher antenna gain. Bands below 10 GHz can be operated increasingly as non-line-of-sight paths as the frequency is decreased, but will be prone to attenuation due to shadowing and multipath. These effects will in general be less than a corresponding terrestrial link at a given frequency.

Propagation models relating to the above frequencies are in development [41–43], but in general lack full practical verification from HAPs. Given the similarity with satellite slant path links, some models, especially relating to rain outage can be accurately extrapolated.

### 1.3.2 Regulatory Environment and Restrictions

The regulatory environment is highly complex as it relates to HAPs, but falls into two main areas:

- **Radio regulation** – mainly dealing with use of the radio spectrum, and prevention of HAPs and corresponding ground equipment from causing harmful interference to other user types sharing the same frequency band.
- **Aeronautical regulation** – mainly dealing with aspects of safety in controlled civilian airspace.

The plethora of regulations that impact on HAPs can present a major challenge to the operation of HAPs depending on one's viewpoint. One perspective is that HAPs are a completely new technology, which requires a whole new regulatory

framework. In fact in the early years of HAPs development this was seen as an advantage, as putting such a regulatory framework in place provided an extra degree of credibility for this emerging technology. SkyStation (USA), NICT (Japan) and ETRI (Korea) spent significant time pursuing new radio regulations (as discussed below) under the auspices of the ITU-R. This did indeed build momentum, but by focusing on regulation also drew attention to the fact that aeronautical regulations pertaining to HAPs were far from clear. For example even today it is not possible to fly an unmanned craft in civilian airspace for safety reasons, although as described below work is underway to develop the necessary regulatory framework. Also anomalies have emerged, e.g. within the ITU-R a high altitude platform station (HAPS) is defined as flying above 20 km altitude, whereas many of the HAPs will fly between 17 km and 20 km, and as such the regulations as developed do not strictly apply. Also, controlled airspace stops above approximately 15 km, so from an aeronautical perspective the airspace is currently unregulated, but it is necessary of course to fly the HAP to this height.

Thus, today there are increasing moves to now focus on the similarity with existing systems and services and apply and or extrapolate existing regulations. Thus, from a radio perspective it may be possible to consider a HAP flying below 20 km as a tall terrestrial mast, making many more potential radio frequency bands available to use. Also, to circumvent the aeronautical regulatory issues of unmanned flight in civilian airspace, manned stratospheric HAPs are attracting considerable attention, as an intermediate evolutionary step.

A third line of thinking, especially by entrepreneurs, is to just go ahead and build HAPs and fly them in a suitable environment (or friendly country) and let the regulations catch up with reality, giving them a head start on any competition. There is some precedent for this; anecdotally the development of the direct broadcast by satellite (DBS) market in the UK by Sky TV in the 1980s shows what is possible by just going ahead and developing a product. A company in Luxembourg was responsible for owning and launching the satellites, and in conjunction with the local regulatory authorities, Sky TV selected an unused frequency that suited their needs from a commercial perspective, but which was not in a band set aside for DBS to the home use. By the time international regulators tried to force Sky TV to pick an alternative frequency, it was no longer really feasible as Sky TV had a customer base in the hundreds of thousands. In parallel, British Satellite Broadcasting (BSB) was following a more conventional regulatory route, and chose to operate in the band set aside for DBS, but which required development of brand new technology, which was subsequently delayed. This delay eventually caused them to be less commercially successful than Sky TV, resulting in their takeover by Sky a couple of years after launch.

So, to sum up, the regulatory environment is in some confusion, which is only to be expected with a brand new technology that has yet to be fully developed. We now

discuss in more detail the two main regulatory areas of radio and aeronautical regulation.

### 1.3.2.1 Radio Regulation

The ITU-R has wide ranging activities concerning spectrum regulation for HAPs. A number of frequency bands have been specified by ITU-R for HAPS (with a narrower definition from that used in this book) [13], and these are included in the successive WRC resolutions:

- 48/47 GHz [13] – 300 MHz bandwidth in both directions – worldwide.
- 31/28 GHz [14] – revised at WRC 07 to 300 MHz in both directions – for use in over 40 countries worldwide (include all countries in North and South America but excluding all of Europe).
- 2 GHz [15] worldwide to support IMT-2000 from HAPS.
- 6 GHz [44] is also under consideration as a WRC 11 Agenda item for Gateway link use for IMT-2000 use.

These activities take place in working parties (e.g. WP9B, WP4-9S, and to a lesser extent WP8F). A list of main current ITU-R recommendations is included in Table 1.1.

**Table 1.1** List of the main ITU-R recommendations on HAPS in January 2010 [45]

Number	Title
F.1500 (05/00)	Preferred characteristics of systems in the fixed service using high altitude platforms operating in the bands 47.2–47.5 GHz and 47.9–48.2 GHz. In force
F.1569 (05/02)	Technical and operational characteristics for the fixed service using high altitude platform stations in the bands 27.5–28.35 GHz and 31.0–31.3 GHz
F.1570 (05/02)	Impact of uplink transmission in the fixed service using high altitude platform stations on the Earth exploration-satellite service (passive) in the 31.3–31.8 GHz band
F.1607 (02/03)	Interference mitigation techniques for use by high altitude platform stations in the 27.5–28.35 GHz and 31.0–31.3 GHz bands
F.1608 (02/03)	Frequency sharing between systems in the fixed service using high altitude platform stations and conventional systems in the fixed service in the bands 47.2–47.5 GHz and 47.9–48.2 GHz
F.1609 (02/03)	Interference evaluation from fixed service systems using high altitude platform stations to conventional fixed service systems in the bands 27.5–28.35 GHz and 31.0–31.3 GHz
F.1609-1 (04/06)	

*(continued)*

**Table 1.1** (Continued)

Number	Title
F.1612 (02/03)	Interference evaluation of the fixed service using high altitude platform stations to protect the radio astronomy service from uplink transmission in high altitude platform station systems in the 31.3–31.8 GHz band
F.1764 (04/06)	Methodology to evaluate interference from fixed service systems using high altitude platform stations to fixed wireless systems in the bands above 3 GHz
F.1819 (09/07)	Protection of the radio astronomy service in the 48.94–49.04 GHz band from unwanted emissions from HAPS in the 47.2–47.5 GHz and 47.9–48.2 GHz bands
F.1820 (09/07)	Power flux-density at international borders for high altitude platform stations providing fixed wireless access services to protect the fixed service in neighbouring countries in the 47.2–47.5 GHz and 47.9–48.2 GHz bands
M.1456 (05/00)	Minimum performance characteristics and operational conditions for high altitude platform stations providing IMT-2000 in the bands 1885–1980 MHz, 2010–2025 MHz and 2110–2170 MHz in Regions 1 and 3 and 1885–1980 MHz and 2110–2160 MHz in Region 2
M.1641 (06/03)	A methodology for co-channel interference evaluation to determine separation distance from a system using high altitude platform stations to a cellular system to provide IMT-2000 service within the boundary of an administration
P.1409 (10/99)	Propagation data and prediction methods required for the design of systems using high altitude platform stations at about 47 GHz
SF.1601 (02/03), SF.1601-1 (04/05) SF.1601-2 (02/07)	A methodology for interference evaluation from the downlink of the fixed service using high altitude platform stations to the uplink of the fixed-satellite service using the geostationary satellites within the band 27.5–28.35 GHz
SF.1843 (2007)	Methodology for determining the power level for high altitude platform stations ground terminals to facilitate sharing with space station receivers in the bands 47.2–47.5 GHz and 47.9–48.2 GHz
SM.1633 (06/03)	Compatibility analysis between a passive service and an active service allocated in adjacent and nearby bands

### 1.3.2.2 Aeronautical Regulation

The original vision for HAPs was that they would be unmanned and capable of fully autonomous control, without a continuous link to Air Traffic Control (ATC). However, this is currently far in advance of current Air Traffic Management (ATM) regulations. They require that one or more pilots are on board an aircraft who must be capable of flying the plane at all times, and while airborne the pilot must have



voice and data communications capability with ATC. The main reason for this is that regulated civilian airspace has become increasingly crowded, so from a safety perspective, pilots are a tried and trusted means of avoiding collisions [46].

Regulators such as the Joint Aviation Authority (JAA) in Europe are currently grappling with this problem for all types of UAV. One possible half-way solution is to have a remote pilot on the ground, who is capable of providing continuous control via a radio/satellite link. However, this may still provide some autonomous control in the event of link failure. Importantly, the trend is to create regulations for unmanned aircraft that will be similar to existing manned aircraft regulations in order to ensure that an unmanned aircraft does not create a greater safety risk to the population or properties or to other manned or unmanned aircraft sharing common airspace, than existing aircraft.

A second issue already alluded to above is the height of current civilian regulated airspace (currently approximately 15 km) [46], which means that currently these stringent regulations do not apply except for launch and recovery phases. A way round the current regulations in launch and recovery phases is also possible if they could take place outside of conventional civilian airspace, e.g. in special designated zones or even military airspace. However, it remains to be seen whether the current height for regulated airspace will remain unchanged if a large number of aircraft start to use it.

Despite the alternative strategies above it is realistically anticipated that the aeronautical regulations will eventually have to cover the following areas [46]:

- System Safety Objectives.
- Tailored 'JAR' code adjusted to the HAP class and application.
- Communication Data Link (electromagnetic protection, security from external intrusion, failure handling and return home procedures).
- Ground control station (Human Machine Interface minimising human errors, safety warnings and indications, failure handling, redundancy, minimum crew required).
- Flight Management System (flight control and navigation, fail safe principles).
- Flight Termination System (autonomous control, predefined emergency recovery sites, gliding capability).
- Emergency electrical power (capacity for emergency landing).
- Hardware and software qualification.

Operational regulations (besides maintenance aspects) should cover [46]:

- Qualification requirements for HAP operators and crew.
- ATC communication capability within the relevant ATM environment.

- Required safety operational equipment (in particular covering ‘Sense/See and Avoid’).
- Emergency procedures.

To help with the above the UK Government is currently financing the ASTRAEA project [47] which aims to help define these regulations and also hardware and software for civil operation of UAVs to facilitate routine UAV operations in civilian airspace in the UK. One of the objectives of the ASTRAEA project is to overcome resistance to operation of unmanned aircraft by the regulators, who want to maintain their excellent safety records. Therefore, it will be required that such craft must prove that they are even safer than conventional manned commercial aircraft.

#### **1.4 Candidate Standards for Provision of Services and Applications from HAPs**

HAPs are seen as a candidate infrastructure for the provision of various types of services and applications to fixed and mobile, individual and group terminals. Their complementary role, or a role in disaster recovery scenarios, requires the use of existing or developing wireless standards, with minimum adaptations to HAP specifics, if needed. This enables the opportunity to reuse existing (off-the-shelf) equipment on HAPs, while on the other hand making use of widespread user terminals. Clearly not the same standard meets optimally all the needs of different services and applications nor operating scenarios, but the capability of HAPs for being landed for payload maintenance, upgrade and/or replacement allows for modular development of complementary payloads that fit different missions.

Currently there are no definite standards that need to be used on HAPs or that would be developed taking into account specific characteristics of HAPs. Provision has been made by ITU-R regarding the use of frequencies in 2 GHz band for the delivery of 3G (IMT-2000) based communications directly from HAPs, whereas true broadband fixed and/or mobile wireless access is confined to millimetre wave band, more precisely to the frequencies at 31/28 GHz and 48/47 GHz with some restrictions. For these frequency bands there are several candidate standards that could serve the purpose [48], in particular IEEE 802 standards (IEEE 802.11, IEEE 802.16 and IEEE 802.20), DOCSIS standards (MMDS and LMDS) and DVB standards (DVB-S/S2, DVB-RCS).

None of the above standards suits perfectly for the service provision via HAPs, hence the choice is driven not only by HAP characteristics but also by targeted services and applications to be provided, business model, operating frequency band, etc. Different frequency bands also infer different link budgets and the use of

techniques to mitigate propagation impairments. Furthermore, with respect to mobile services the respective standard used should support mobility management and operation in the presence of Doppler frequency shifts.

Important criteria in selection of a communication standard are also its flexibility, i.e. the degree of freedom it allows to adapt the system to the specific needs while staying within the predefined specifications, and the openness of the standardisation process, giving an opportunity to influence the decisions of standardisation body or propose potential adaptation of specifications for specific operating environment. In the following some candidate standards are briefly reviewed focusing on broadband wireless access standards and their suitability for delivery of services and applications from HAPs.

#### *1.4.1 Mobile Cellular Standards*

The use of cellular standards from HAPs is generally seen as one of the more acceptable and feasible scenarios, particularly in the light of allocated frequencies in the 2 GHz frequency band to support IMT-2000 services from HAPs. This actually spurred a number of studies investigating the performance of 3G standards on HAPs starting from the earlier ones focusing on UMTS and W-CDMA in general [18, 49–53] to more recent investigating the performance of HSDPA from HAPs [54, 55]. These studies started in parallel or superseded studies on the use of 2G technologies, most notably GSM [56–58], mainly conducted in the frame of or related to the European FP5 IST project HeliNet [59, 60]. Obviously, the focus in these studies shifted from cellular radio network planning and efficient management of radio resources in GSM related studies to interference and system capacity investigation in 3G related studies.

In order to become a technology of choice, HAPs will have to make their way into next generation mobile technologies known as IMT Advanced. The best known representatives of the IMT Advanced set of standards are the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) and LTE-Advanced (LTE-A). LTE is focusing on the evolution of the 3GPP radio technologies, concretely UMTS, towards 4G, whereas LTE-A is intended to adapt LTE to the requirements of 4G [61]. For these standards no particular radio frequency provision has been made for the use on HAPs. Moreover, the radio regulation does not appear to be keen in making any further spectrum allocations for HAP systems due to the absence of commercially available aerial platforms. For HAP systems it is thus important that radio regulation adopts a sufficiently flexible spectrum licensing strategy to ensure that the future potential of HAPs, or any other technically sound technology, is not prevented from entering into operation once aerial platforms become commercially viable [62].

In general, a standalone implementation of any cellular standard on HAP should not represent a major obstacle for instance for initial roll-out of a service or in case of major disaster relief, since an aerial platform flying at the altitude around 20 km and equipped with a base station can be seen as a tall mast. However, coexistence of HAP and terrestrial systems renders problems in radio network planning and interference avoidance. The coverage of terrestrial cells is largely influenced by various obstacles such as buildings, trees, hills, etc., whereas comparatively large HAP cells are only shaped by the antenna pattern. Thus a HAP-based base station, although representing a secondary system, can potentially cause much higher interference to terrestrial primary systems than vice versa, which calls for the development and utilisation of interference avoidance techniques. These problems are recently being investigated from the perspective of cognitive radio and dynamic spectrum assignment, which may play an important role in interference avoidance and consequently adoption of HAP systems.

#### *1.4.2 IEEE 802 Wireless Standards*

IEEE 802 has developed an alternative series of wireless Internet standards [63]. The main intent is to bring to market low-cost products that serve customer needs. Much of the work involves license-exempt spectrum, which removes the spectrum acquisition costs from the economic picture. Furthermore, it weakens the concept of a monolithic ‘operator’ with strong control over the provided services. Instead, it opens up the market to enterprise and innovation.

IEEE 802 wireless Internet technologies mostly offer data rates much higher than those provided by even the fixed user case in IMT-2000. However, the basic structures of IEEE standards were not intended to offer the mobility of IMT-2000 in the sense of providing services to moving vehicles. However, extensions to high mobility have been defined for IEEE 802.16 whereas IEEE 802.20 was from the start developed as a standard for mobile broadband wireless access.

IEEE 802 LAN/MAN Standards Committee [64] has developed separate standardisation branches for Wireless Metropolitan Area Network (WMAN), Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN), and more recently with the transition towards digital TV and subsequent release of analogue TV frequency bands also Wireless Regional Area Network (WRAN):

- WMAN includes IEEE 802.16 and IEEE 802.20 standards, which support high-rate broadband-wireless-access services to fixed and mobile users from central base stations.
- WLAN denotes the IEEE 802.11 set of standards, which support users roaming within homes, office buildings, campuses, hotels, airports, restaurants, cafes, etc.

- WPAN, represented by IEEE 802.15 standards, is intended for the support of short-range links among computers, mobile telephones, peripherals, and other consumer electronics devices that are worn or carried.
- WRAN is defined by IEEE 802.22 standard for a cognitive radio-based PHY/MAC/air interface for use by license-exempt devices on a noninterfering basis in spectrum that is allocated to the TV Broadcast Service.

IEEE 802.11 and 802.15 have worked particularly closely since they both address unlicensed bands. IEEE 802.16 has historically dealt with licensed bands and been more independent. The work on IEEE 802.20 originally started almost in parallel with the amendment to IEEE 802.16e to enable connections for mobile devices, but aimed at higher speeds of terminals and higher throughputs. IEEE 802.22 is technically the most advanced standard and the first to include the concept of cognitive radio for better exploitation of shared frequency spectrum.

#### 1.4.2.1 IEEE 802.11

The IEEE 802.11 working group is working on an evolving family of specifications using the Ethernet protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for path sharing. Originally it started with a standard describing MAC (Medium Access Control) sublayer and three PHYs (PHYSical layers), which are now obsolete, but served as a baseline for subsequent amendments that:

- Describe several Wireless LAN PHYs, which differ in transmission techniques and consequently in maximum throughput, all operating in the unlicensed band at 2.4 GHz or at 5–6 GHz.
- Enhance original MAC and MAC-management functionality to provide expanded international operation and roaming, improved support for quality of service, dynamic channel selection, transmit power control, and an architecture and protocol that support both broadcast/multicast and unicast delivery and mesh networking.
- Offer additional security for WLAN applications and define more robust encryption, authentication and key exchange.

The crucial role in widespread adoption and interworking of devices based on the IEEE 802.11 standards played the Wi-Fi Alliance [65]. The term Wi-Fi is often used as a synonym for IEEE 802.11 technology, because of the close relationship with its underlying standard.

IEEE 802.11 standards are mainly intended for use in short-range point-to-point configurations, so they are not particularly suitable for HAPs. On the other hand, Wi-Fi certification guaranteeing compatibility and interoperability of devices based on the 802.11 specification, low equipment price, the availability of off-the-shelf components and easiness of set-up may be appealing for the use of adapted IEEE 802.11-based solutions with extended range. For broadband wireless access provision via HAPs the signal may need to be upconverted to mm-wave frequencies, whereas for rapid establishment of ad hoc networks in emergency scenarios the equipment may as well be used in its nominal band. There are several studies reporting on range extension of WLAN networks, however, data rates achieved in such adapted systems are rather low and are not likely to justify system implementation and HAP deployment. The IEEE 802.11b protocol, in particular, seems to be adaptable to HAP operating environment. This was demonstrated by the CAPANINA project during its second year trial [66] using an 802.11 base station with carrier frequency conversion to the 28 GHz and a high gain tracking reflector antenna at the ground station. The achieved bit rate, however, was low, in the CAPANINA trial most of the time below 1 Mbit/s, and the standard is not suitable for high-speed mobility environments. This low data rate was achieved by adjusting the acknowledgement time-outs, in order to cope with long range links. These longer round-trip times results in a much larger proportion of the transmit–receive duty cycle being wasted, resulting in the lower throughputs than seen with conventionally short-range Wi-Fi systems.

#### 1.4.2.2 IEEE 802.16

IEEE standard 802.16 was designed to evolve as a set of air interfaces based on a common MAC protocol, while PHY layer specifications depend on the used spectrum and associated regulations [67]. Typical applications that can be supported by the IEEE 802.16 access system include applications and services such as digital audio/video multicast, digital telephony, ATM cell relay, IP datagram transfer, back-haul service for cellular or digital wireless telephone networks, virtual point-to-point connections, and frame relay service.

The initial standard, based on a single carrier technology with adaptive modulation and coding schemes only addressed frequencies from 10 to 66 GHz, where extensive spectrum is currently still available worldwide. It assumed line-of-sight (LOS) propagation with no significant concern over multipath propagation. Offered capacities and addressed frequency bands make this standard particularly well suited for use on HAPs. The main concerns about this standard derive from the fact that it was developed for LOS conditions and fixed wireless access only.

Amendment IEEE 802.16a (WirelessMAN) to the initial standard has extended the air interface support to lower frequencies in the 2–11 GHz band so as to allow

non-LOS operation and robustness to significant multipath propagation. Compared with the higher frequencies, such spectra offer the opportunity to reach many more customers less expensively, although at generally lower data rates. Operating in the 2–11 GHz band three PHYs have been developed, one again based on a single carrier technology, one using OFDM with a 256-point FFT and one based on OFDMA with a 2040-point FFT. The combined the initial standard for 10–66 GHz and WirelessMAN amendment formed the Air Interface for Fixed Broadband Wireless Access System denoted as IEEE 802.16-2004.

A further amendment, IEEE 802.16e, extended PHY and MAC layers of WirelessMAN-OFDM for combined fixed and mobile operation in the 2–6 GHz licensed frequency bands. It is aimed at supporting bit rates up to 15 Mbit/s to mobile subscriber station with nomadic mobility up to approximately 100 km/h. Fixed and mobile standards along with the management plane related amendments were eventually brought together in the standard IEEE 802.16-2009 entitled ‘Air Interface for Fixed and Mobile Broadband Wireless Access System’.

A particularly important role for the acceptance and implementation of IEEE 802.16 standard equipment is played by the global standard and interoperability forum WiMAX [68]. This forum is also certifying the compliance of equipment with adopted specifications. Thus, WiMAX is to IEEE 802.16 what Wi-Fi is to IEEE 802.11. In fact, the terms WiMAX and mobile WiMAX became synonyms for the fixed and mobile versions of WirelessMAN standard.

Being developed for broadband wireless access the IEEE 802.16 protocol family appears as the most suitable option for broadband service delivery via HAPs. It can be used in a point-to-multipoint topology to link commercial and residential buildings to high-rate core networks, thus resolving the ‘last mile’ problem of the Internet connection. Furthermore, IEEE 802.16 variants specify different air interfaces for operating in frequency bands between 2 GHz and 66 GHz, thus covering all HAPs allocated bands. However, the upper frequency bands are only covered by the variant for fixed services, whereas extensions for mobility management are only standardised for the frequencies below 6 GHz, thus only available for exploitation from HAPs should frequencies below 6 GHz become available also for HAPs. In fact, there has been a significant body of research work on WiMAX provision from HAPs conducted in the European COST Action 297 [35], many studies focusing on the coexistence of terrestrial and HAP-based WiMAX services.

#### **1.4.2.3 IEEE 802.20**

IEEE 802.20 Working Group was concerned with the development of a IEEE 802 based standard for the Mobile Broadband Wireless Access (MBWA) that meets the needs of business and residential end user markets. The 802.20 technology evolved

as pure mobile and optimised for IP-based services. The standard was eventually approved by the IEEE as IEEE 802.20-2008 and its scope consists of the physical, medium access control (MAC) and logical link control (LLC) layers. The new air interface was developed for the operation in licensed bands below 3.5 GHz with peak data rates per user in excess of 1 Mbit/s. It supports various vehicular mobility classes up to 250 km/h, and spectral efficiencies, sustained user data rates and numbers of active users that are all significantly higher than achieved by existing mobile systems. This standard thus seems attractive, should frequencies below 3.5 GHz ever become available for the use on HAPs. An important drawback is the fact that the technology is not widely spread, so user terminals are not broadly available to date.

#### *1.4.3 Multipoint Distribution Services for Multimedia Applications – MMDS and LMDS*

By restricting the scope of HAPs to delivery of asymmetric broadband services for fixed users only, two further standards appear interesting for the use on HAPs, the Local Multipoint Distribution Services (LMDS) and Multichannel Multipoint Distribution Services (MMDS). LMDS and MMDS have adapted the DOCSIS (Data Over Cable Service Interface Specification) from the cable modem world. The version of DOCSIS modified for wireless broadband is known as DOCSIS + . LMDS and MMDS wireless modems utilise the DOCSIS + key-management protocol to obtain authorisation and traffic encryption material, and to support periodic reauthorisation and key refresh.

DOCSIS + incorporates the DOCSIS standard in both the MAC and PHY layers to support robust wireless operation. The air interface enables service providers to increase subscriber coverage through near-LOS operation and supports assured quality of service.

The unidirectional MMDS is a wireless network for delivery of broadcast video programs or data information. The bidirectional MMDS can be used to transport two-way data, video, and voice information. MMDS is primarily a LOS microwave-based transport technology, in which the antenna broadcasts the signals towards the end users, typically within a small regional area in the order of up to 50 km. The customer's premise is equipped with an MMDS antenna, a radio frequency transceiver, and a Set Top Box. The frequency spectrum for MMDS system is below 10 GHz, typically in the range of 2–3 GHz. The bandwidth for MMDS is typically in the order of 200 MHz.

The LMDS is a one- or two-way wireless system for data, video and telephony. The unidirectional LMDS is mainly addressing video broadcasting applications, whereas a two-way LMDS system allows for interactive services. LMDS is also a LOS microwave-based transport technology, typically serving a very small



regional area in the order of a few kilometres. However, LMDS uses much higher radio frequencies than MMDS, since these systems operate at frequencies above 10 GHz, typically between 26 GHz and 31 GHz; as a consequence LMDS has more bandwidth, typically in the order of 1 or 2 GHz.

Being developed for multipoint distribution services, MMDS and LMDS are particularly appealing for the provision of asymmetric broadcast/multicast services to fixed users via HAPs, LMDS in particular due to the operating frequency band similar to that of HAPs. However, both MMDS and LMDS are suitable for the provision of services and applications to fixed users only, and they appear to have been made obsolete by WiMAX and IEEE 802.16-SC standards.

#### *1.4.4 DVB Standards*

DVB specifications cover all aspects related to the audio, video and data signals broadcasting over a variety of transmission physical media. With the use of an interaction channel for return link these standards, originally developed for broadcasting services, also appear potential candidates for delivery of broadband communications via HAPs. Due to some similarities between satellites and HAPs a combination of DVB-S [69] or DVB-S2 [70] and DVB-RCS [71] standards developed for single carrier systems operating at frequencies above 10 GHz proves to be a particularly interesting candidate.

The satellite DVB standards have several appealing characteristics for the use on HAPs, particularly the supported data rates on the forward link (downlink), support for adaptive coding and modulation, native point-to-multipoint operation, and high operating frequency bands including those covering HAP allocated frequencies. The use of satellite DVB standards on HAPs would be particularly suitable in the case of integrated satellite and HAPs networks [72, 73]. The main drawbacks are the relatively low data rate supported on the return link (uplink), thus only asymmetric applications can be supported, requirement for the LOS channel conditions and no explicit support for mobility management. The combination of DVB-S2 and DVB-RCS standards [74] for the use on HAPs has been investigated in several studies with particular attention on the implementation and performance evaluation of adaptive coding and modulation [75–79].

##### **1.4.4.1 DVB-S/S2**

The Digital Video Broadcasting-Satellite (DVB-S) determines the standard for satellite broadcasting and for the supply of multimedia services [69]. DVB-S is the oldest and most widespread of the DVB specifications family, making the basic DVB-S techniques proven and mature. DVB-S is being used for point-to-point,

point-to-multipoint and mobile satellite data communications systems. A major advantage of the digital DVB-S platform is its ability to provide broadcast transmission of a large volume of data at a very high rate and with an excellent protection against a variety of transmission errors.

The outdated DVB-S standard has been replaced by DVB-S2 standard [70]. It is characterised by variable coding and modulation functionality, which allows different modulations and error protection levels to be used and changed on a frame-by-frame basis. Combined with the use of a return channel this may be used for closed-loop adaptive coding and modulation (ACM), allowing the transmission parameters to be optimised for each individual user and his propagation path conditions. DVB-S2 is capable of accommodating any input stream format, including continuous bit streams, single or multiple MPEG Transport Streams, native IP as well as ATM packets.

DVB-S2 does not explicitly specify symbol rate range. However, implementations by different vendors can cover maximum transmission rates as high as 300 Mbit/s. The combination of DVB-S2 and DVB-RCS can also be adapted to support full mesh network topology.

#### **1.4.4.2 DVB-RCS**

In order to support interactive satellite applications the DVB Project has defined a specification for the return channel via satellite, the DVB-RCS [71]. It supports symbol rates in the range from 128 ksymbol/s to 4 Msymbol/s, resulting in return link information bit rates beyond 5 Mbit/s, for some modes even over 10 Mbit/s.

The DVB-RCS specification was designed to support quality of service (QoS) for a variety of applications over the satellite link and defines a variety of bandwidth allocation mechanisms. Thus, each terminal can have multiple virtual channel assignments with different QoS parameters. Supported bandwidth allocation mechanisms include: continuous rate assignment, rate based dynamic capacity, volume based dynamic capacity, absolute volume based dynamic capacity, and free capacity assignment.

The DVB-RCS specification also defines provisions for security, in particular DVB common scrambling in the forward link, satellite interactive network individual user scrambling in the forward and return link, IP network security (IPsec) and higher layer application security mechanisms.

### **1.5 Overview of Past and Present HAP Related Projects, Trials and Development Plans**

This section provides more detailed information of the major HAPs projects and players, some of which have already been briefly discussed above in Section 1.2. We

focus here on their major achievements, including trials and demonstrations, and if they are still ongoing their future plans, where these are publicly available.

### 1.5.1 StratXX AG – X-Station

This project is developing a solar powered airship based HAP, the X-Station [33]. They are ‘striving to commercialise stratospheric communication platforms through the innovative application of advanced technologies’, including the rapid provision of communications systems using HAPs in regions currently not well served or lacking infrastructure. They plan to deploy a number of services on their platform, capable of providing, TV and radio, broadcast, mobile telephony, Voice over Internet Protocol (VoIP), remote sensing and local GPS. To date they have developed lower altitude airship-based platforms, including PhoeniXX and X-BUGS, and a photograph of one of their airships in development is shown in Figure 1.5. The test programme involved testing both the craft and the communications and remote sensing payloads.



**Figure 1.5** StratXX X-Station Airship in development in 2007 [33]. Reproduced by permission of © StratXX Near Space Technologies AG

StratXX is located in Switzerland, and it uses a number of European strategic partners from industry and academia, including CSEM (Switzerland), DLR (Germany), EPFL (Switzerland), RUAG Aerospace (Switzerland), and University of York (UK), as well as its own in-house expertise.

### 1.5.2 ERS srl

ERS srl [34] is a small Italian company that is planning to initially use stratospheric manned plane-based technologies, including the Grob G520T and G600, to deliver a range of services from communications and remote sensing payloads. ERS is one of the few companies with actual experience of flying payloads in the stratosphere. Over the last decade they have been responsible for a number of scientific experiments using the M55 Geophysica, a Russian built stratospheric plane.

### 1.5.3 CAPANINA

The European Commission supported the CAPANINA project (FP6-IST-2003-506745) [28] as part of the 6th Framework Programme, to further develop the state-of-the-art in broadband from aerial platforms. The project ran from November 2003 until January 2007, involving a consortium of 13 partners, representing a mixture of large industry, SMEs, and academia/research organisations.<sup>1</sup>

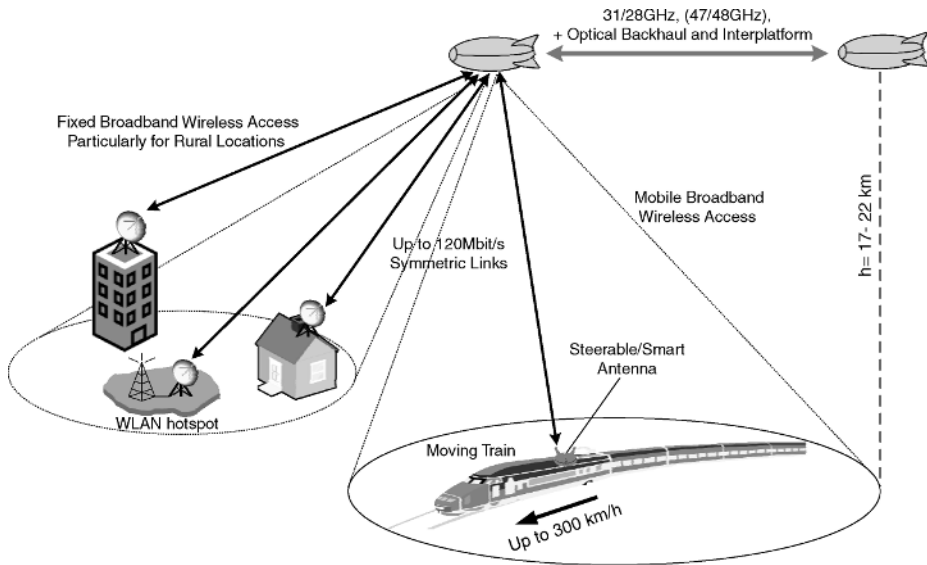
CAPANINA focused on development of low-cost broadband technology from HAPs aimed at providing efficient coverage to users who may be marginalised by geography, distance from infrastructure, or those travelling inside high-speed public transport vehicles (e.g. trains travelling up to 300 km/h) [28], as shown in Figure 1.6. The aim was to exploit this future wireless technology to deliver burst data rates to users of up to 120 Mbps anywhere within a 60 km coverage area. Both mm-wave band and free space optical communications technologies were considered.

The project adopted a three-strand approach:

- Identification of appropriate applications and services and associated business models. This included establishing the most appropriate integrated network architectures, and included wireless and free space optical link technologies, and multiple platform technologies and spectrum sharing.
- The development of a system testbed that allowed nearer-term tests of broadband services/applications to fixed users, including backhaul for terrestrial WLAN, corporate communications and video-on-demand, along with an evaluation of free space optical technology.
- Longer-term state-of-the-art research and innovation that examined advanced mobile broadband wireless access. Outline system design and critical hardware

---

<sup>1</sup> The CAPANINA Partners were: University of York (UK), Jožef Stefan Institute (Slovenia), Politecnico di Torino (Italy), Universitat Politècnica de Catalunya (Spain), Carlo Gavazzi Space (Italy), Budapest University of Technology & Economics (Hungary), DLR (Germany), BTexact (UK), EuroConcepts Srl (Italy), CSEM (Switzerland), Contraves AG (Switzerland), National Institute of Information & Communications Technology (Japan), and Japan Stratosphere Communications (Japan).



**Figure 1.6** CAPANINA project scenario

was developed for a scenario that delivered broadband to trains, integrating with on-board wireless LAN base stations.

The project delivered a number of trials with different types of HAP.

Trial 1 [28, 80] took place between August 2004 and October 2004 in Pershore, UK. A spherical aerostat, capable of operating at an altitude of 300 m was used. The following aspects were successfully demonstrated:

- Broadband Fixed Wireless Access (BFWA) up to a fixed user using 28 GHz band.
- Demonstration of end-to-end network connectivity.
- Demonstration of services such as high speed internet and video-on-demand.
- Optical communications – HAP to ground – simplified overall system without beacons to perform first ground station tracking tests.

These tests were carried out at low wind speeds since the spherical aerostat was less aerodynamically stable than the more conventional teardrop shape.

Trial 2 [80] took place in August 2005 near Kiruna, Sweden using a stratospheric balloon for a short term, one off mission of 9 h. The following aspects were demonstrated:

- A broadband wireless link and applications. Using an updated mm-wave WLAN payload with on board server, a number of broadband applications were tested, such as video download and web-page download. Channel rates were limited by the IEEE 802.11b technology used at the time. This payload used the 28/29 GHz bands, within band allocations permitted by the Swedish authorities. To overcome the problems of the lack of station-keeping on a free flying balloon, wide area coverage from the balloon was achieved using a lens antenna. A tracking antenna on the ground was used to achieve the link budget.
- Optical Communications
  - The first known 1.25 Gbit/s HAP to ground link was tested. This was achieved using on board optical laser tracking to cope with the balloon's station keeping, and a tracking optical receiver on the ground, based on an astronomical telescope [81].
  - Measurements of the turbulence of the optical channel were tested, and compared with simulation
- Integration of a multi-payload system on a Stratospheric Carrier, subject to low temperature, low air density, higher levels of radiation than on the ground, challenging weight and power constraints.

Trial 3 [82] took place in November 2006 in Paso Robles, California, USA using the AeroVironment (AV) Global Observer 1/5 scaled-size prototype, with direct support from AV and NICT, Japan. This trial was limited in scope owing to the fact that the prototype was limited to low altitude flight. The project used it to test station-keeping and altitude models and also examine the capabilities of low altitude UAV to support localisation of signals from the ground, such as may be required in disaster scenarios.

#### 1.5.4 USEHAAS

USEHAAS [83] was a European FP6 Specific Support Action under Aeronautics and Space Priority that ran from March 2005 to October 2006. It aimed to examine prospective aeronautical research agendas in High Altitude Aircraft and Airships (HAAS), along with associated mission/applications in conjunction with the European aeronautical and space industry.

Sub-objectives included:

- To analyse the world state of the art including European work relating to HAAS aeronautical uses, as well as the programmes and tests underway in USA, Europe, Japan, China and Korea.

- To develop tentative Research Objectives for European/Global HAAS Deployment regarding a variety of end-user services and prepare an outline of a potential aeronautical research programme.
- To disseminate recommendations on the Objectives and the Aeronautical Research Agenda.
- To issue a final version of the Specific Research agenda, including the impact on regulations and recommendations on such a call. It may assemble the activities in the sector, and provide appropriate technological roadmaps based on inputs made during the workshops and working groups with end users and possible industrial partners

### *1.5.5 COST 297*

COST 297 [35], which has recently concluded, provided a forum for research and technological development into HAP communications and other services. Its main objective was: ‘To increase knowledge and understanding of the use of High Altitude Platforms (HAPs) for delivery of communications and other services, by exploring, researching and developing new methods, analyses, techniques and strategies for developers, service providers, system integrators and regulators.’

Activity was divided into three working groups:

- WG1 Radio Communications;
- WG2 Optical Communications;
- WG3 Aerial Platforms.

### *1.5.6 The Japanese National Project*

This government funded millennium project commenced in 1998, with the primary splits being between aeronautics, telecommunications, and earth observation. The Japan Aerospace Exploration Agency (JAXA) was coordinating the aeronautics aspects, with the telecommunications activities under the coordination of National Institute of Information and Communications Technology (NICT). The aeronautics and telecommunications activities are described separately below.

#### **1.5.6.1 Japan Aerospace Exploration Agency (JAXA)**

JAXA (formerly the National Aerospace Laboratory) has had several significant technical achievements. These have mainly been centred on the launch and landing

phases of the stratospheric airship, which are seen as the most difficult aspects, airship materials and construction, station-keeping and power management. More specifically:

- Basic research into the properties of airship materials and construction techniques suitable for long-term stratospheric flights.
- Regenerative fuel cell (RFC) and solar power research and development. They currently have a RFC working prototype capable of delivering 400 Wh/kg and have a design on the drawing board to deliver 700 Wh/kg.
- Airship deflation tests using small explosive charges, to open up a hole in the envelope to ensure controlled decent.

This research and development was used in two major experiments:

- August 2003 – they successfully launched vertically an unmanned 47 m long airship shaped balloon (using ATG's patented launch sequence), at Hitachi Port in Ibaraki, Japan. Under test were the buoyancy control and deflation strategies. The balloon reached the 16.4 km test altitude, where the deflation strategy described previously was used to successfully bring the balloon back to earth in conjunction with a parachute. Additionally, the experiments enabled JAXA to operate a simple payload that was responsible for the collection and analysis of greenhouse gases in the atmosphere.
- November 2004 – they successfully completed tests of an unmanned remotely/automatically piloted 67 m long airship carried out at 4 km altitude, at the Taiki test range in Hokkaido, Japan. The craft had a payload weight capability of 400 kg, including the mission battery. Tests included:
  - heat and buoyancy control;
  - station keeping;
  - ground handling;
  - establishment of a flight operations system;
  - observation of vegetation and traffic system from the airship;
  - telecommunications tests (described below).

#### **1.5.6.2 National Institute of Information and Communications Technology (NICT)**

NICT, formerly Communications Research Laboratory of Japan (CRL) and Telecommunications Advancement Organisation (TAO), has been active in the National Project since its inception in 1998.

NICT has concentrated on communications, broadcasting and radiolocation payloads [84] on HAPs, with the end applications being:



- Disaster relief/event servicing, both 3G and broadband.
- Broadcast HDTV.
- Broadband fixed access to users.
- Broadband mobile access to long distance trains and other vehicles.

These applications were selected primarily because HAPs have the potential to provide users over a wide area with various services at reasonable cost. For example, the project has calculated that 15 000 HDTV terrestrial transmitters are needed to deliver broadcast TV over Japan's mountainous terrain, which can be delivered with around 15 HAPs.

In close coordination and cooperation with JAXA, they have examined tracking and control techniques for stratospheric flight [85], and developed the following hardware for use with experiments:

- Mechanical antenna beamsteering for a multibeam horn antenna at 47/48 GHz.
- A 31/28 GHz digital beamforming (DBF) antenna, capable of delivering 9 Mbps to nine fixed beams and three adaptive beams. They are currently working on a new version that will deliver data rates in excess of 50 Mbps.
- UHF antenna for broadcast HDTV.
- Radiolocation payload.
- Free space optical transmitter and receiver.

These have formed the core of a number of experiments:

- June–July 2002 – World first telecommunications trials using NASA's Pathfinder-Plus solar powered aircraft in Kauai, Hawaii, USA at approximately 20 km altitude, as shown in Figure 1.7. 3G [86] and HDTV [87] applications were demonstrated and specific tests included:
  - Technical data for the operation of equipment in the stratosphere, including temperature, wind speed, and station-keeping behaviour
  - Interference suppression using on-board array antenna at 2 GHz.
  - HDTV transmission with 1 W transmission power.
  - Video connection to off-the-shelf terrestrial 3G (W-CDMA) videophone.
- November 2002 – Video-on-demand, IP phone, Web access and HDTV video transmission were demonstrated [88]. Tests of both the DBF and multibeam horn antennas on a helicopter at 3 km altitude. Specific tests included:
  - multibeam forming;
  - remote array calibration;
  - beam steering and tracking;
  - beam stabilisation;
  - link performance.



NASA Dryden Flight Research Center Photo Collection  
<http://www.dfrc.nasa.gov/gallery/photo/index.html>  
 NASA photo: ED02-0161-2 Date: June 24,2002 Photo by: Nick Galante

Pathfinder-Plus flight in Hawaii

**Figure 1.7** Pathfinder-Plus carrying onboard equipment. Reproduced from NASA – <http://www.dfrc.nasa.gov/gallery/photo/index.html>

- September–November 2004 – Digital broadcasting [89], radiolocation [90] and optical communications [91] were demonstrated from a low altitude airship (see Section 1.5.6.1 for more details on the aeronautics aspects). Specific tests included:
  - Evaluation of airship to ground channel at 2 GHz.
  - Evaluation of coverage, using conventional digital HDTV receivers.
  - Radio location from platform to ground.
  - Free space optical communications ground-platform (acquisition and tracking only).

NICT used the AV Global Observer 1/5 scaled-prototype in November 2006 (also in conjunction with CAPANINA), as discussed previously.

They have also continued to test on a smaller scale a number of aspects using a Zeppelin NT in Japan, including:

- New version of DBF antenna for the 31/28 GHz band.
- Radiolocation.

Spectrum regulation is the second area where the Japanese project has had significant impact. NICT is active on several ITU-R Working Parties, e.g. WP9B, and has been responsible for originating six ITU-R Recommendations, and

contributing to others originated by, for example, SkyStation and ETRI Korea. It has been instrumental in opening up the 31/28 GHz spectrum to HAPs for secondary status at the WRC in 2000 [92].

### 1.5.6.3 Discussion

The Japanese National Project has spent in excess of \$100M since its inception in 1998, although funding is now at a low level. It is the undisputed world leader in HAP communications hardware development and trials, probably achieving more than all other HAP projects put together. The key personnel involved in the project believe HAPs will only succeed in Japan and Asia if they succeed on a worldwide basis. They see the ITU-R and spectrum regulation as being a significant building block. Their abilities to get spectrum licensed in the 31/28 GHz bands originally in Region 3, but later extending to 40 countries worldwide is an important way of HAPs gaining credibility. They have also used partnerships, e.g. with NASA/Japan Stratosphere Communications (JSC) and CAPANINA to help fill in gaps in their expertise. Collaboration with JSC enabled stratospheric trials to be carried out where several world firsts have been achieved. This approach has been used because Japan's airship programme was at a different stage of maturity to communications.

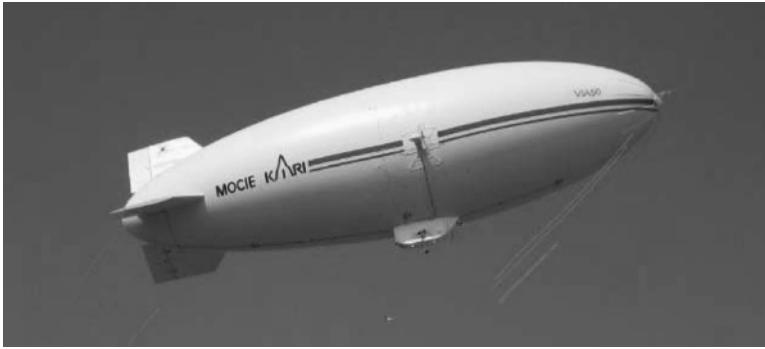
### 1.5.7 *The Korean National Project*

The Korean national activities have been running for a number of years. They are split into the aeronautics part coordinated by the Korean Aerospace Research Institute (KARI), which has been running since December 2000, research and development aspects of communications coordinated by the Electronics and Telecommunications Research Institute (ETRI) which has been running since February 2002, and analysis of communications services by SK Telecom [93]. We now describe each aspect of the project.

#### 1.5.7.1 Korean Aerospace Research Institute (KARI)

The Korean project has a 10-year plan to build an unmanned stratospheric airship capable of supplying 10 kW of power to a payload, weighing up to 1 t. The activities commenced in December 2000.

The project included the development and test of a 50 m unmanned airship, capable of flying to an altitude of 3 km height and carrying a 100 kg payload, as shown in Figure 1.8. This phase of development also included:



**Figure 1.8** The 50 m long unmanned airship developed by KARI for Phase 1. Photograph courtesy of Korean Aerospace Research Institute, Airship Department [94]. Reproduced by permission of © Korean Aerospace Research Institute

- Building of ground facilities including a large hanger in Goheung in the far South of Korea.
- The development and test of electric motors to power the vehicle.
- Launch, landing and station keeping.
- Safety critical systems, including the transfer of control between automatic and manual control.
- Communication system tests.
- Power management of a regenerative fuel cell.
- Basic research into high strength materials, heat management and operational technology for large airships.

#### **1.5.7.2 Electronics and Communications Research Institute (ETRI)**

ETRI's activities commenced in February 2002. They included analysis of possible HAPs services and business models [95] for the Korean market, as well as the development of core technologies [96]. The Institute has been very active in the ITU-R working parties 9B, 9D, and 4-9S, which cover HAPs and has originated (and contributed to) several of the ITU-R Recommendations in force on HAPs. Additionally it has played an important role within WRC 2003, where it was instrumental in extending the use of 28/31 GHz for secondary use within Region 2. Additionally it has also produced material to support WRC 2003 Resolution #734 to extend the frequency bands beyond those currently allocated [97].

Core technologies and studies developed include:

- Development of a direct beam forming multibeam receiving system for S and Ka band.
- Development of mechanical beam steering for 47/48 GHz horn antennas.
- Interference analysis and sharing studies for WCDMA.
- Interference analysis and sharing studies for 28/31 GHz and 47/48 GHz.

### **1.5.7.3 Discussion**

The Korean National Project is one of the most significant research led projects around the world. Its work so far has contributed on a technical basis at the highest level, and its activity within the ITU is extremely significant, with ETRI responsible for much of the pressure to get the 28/31 GHz bands licensed in Asian countries. Additionally, its work in trying to extend the allocated frequencies beyond the existing bands, in order to support WRC 2003 Resolution #734 is world leading.

### *1.5.8 NASA Activity*

NASA has been responsible for building a variety of high altitude plane-based craft, including the Pathfinder, the Pathfinder Plus and Helios, which were developed as part of the ERAST programme [98]. Helios currently has the altitude record of some 98 863 ft established in July 2001. As mentioned earlier it subsequently suffered a ‘mishap’ in which the vehicle was lost. At the time of loss the vehicle was carrying a 250 kg fuel cell beneath the central part of the wing. The resulting investigation has attributed the loss of the craft to a flexing of the wing, caused by the payload being too heavy for the particular design of the craft. This flexing caused lift to be lost and the vehicle to stall, causing the loss of the craft [31]. The investigation has resulted in new recommendations for the design of future vehicles, with the outcome that future designs will be based on the more conventional fuselage, wing and control surfaces (see below), and less reliant on the unique ‘flying wing’ designs used in the Pathfinder Plus and Helios. More details can be found in [98].

#### **1.5.8.1 Discussion**

NASA’s track record on the development of specialist aeronautical vehicles is strong, and is one of a few organisations worldwide that have stratospheric vehicles. They are capable of supporting communications applications, with event servicing/ disaster relief applications being possible in near term, with more permanent applications being possible in the longer term.

### 1.5.9 AV Inc

AV Inc (formerly AeroVironment) [30] started life as a spin-off company of NASA whose objective is to exploit and commercialise NASA technology. It has for a number of years been commercialising NASA's UAV activities. It has specific interests in high altitude planes and is currently developing the energy technology to provide around the clock powered flight, based on hydrogen fuel cell technology. It has built a scaled-size prototype of the latest craft, the Global Observer, and has demonstrated flights of up to 5 days using fuel cell technology. It is also interested in providing round the clock solar powered flight based on a combination of solar powered arrays and regenerative fuel cells. AV Inc has a full size fuel cell and electrolyser storage system for such craft operating in its test facilities.

The craft themselves are aimed at telecommunications, remote sensing and atmospheric measurement. AV Inc has a long term interest, via the spin-off company SkyTower Inc, to deliver a range of applications such as:

- Fixed Broadband
- 3G-Mobile
- Narrowband
- Direct Broadcast
- Event servicing.

It has been pursuing market opportunities on a worldwide basis, and has been specifically targeting developing countries, where there is an absence of infrastructure.

In July 2002, it was jointly responsible for providing the successful tests of various communications for the Japanese National Project (as discussed in Section 1.5.6).

#### 1.5.9.1 Discussion

AV Inc is a significant player in the commercialisation of HAPs. It has detailed business models and excellent technical capabilities. It is also one of the few companies worldwide that has the proven capabilities to launch such a mission and its on-going research programmes into energy storage could prove critical in the development of HAPs.

The Helios mishap has slowed down their marketing of this technology. The fuel cell critical to round the clock deployment was being tested when Helios failed. This delay has also allowed the business models to be revised towards shorter-range missions such as event servicing and disaster relief communications, which are less reliant on solar-powered flight and advanced energy storage, and as such providing a less risky initial exploitation path.

### 1.5.10 Lockheed Martin, Boeing and Worldwide Aeros

Lockheed Martin, Boeing and Worldwide Aeros (USA) have completed Phase 1 of a large development programme as a result of the US Homeland Defense initiative [8, 9, 32]. Lockheed is now proceeding with Phase 2 of the project [99] and has \$40M to develop a solar-powered High Altitude Airship (HAA). The airship is planned to have a mission life of 1 month, operating at 65 000 ft (approximately 20 km), while providing 10 kW of power to a 4000 pound (approximately 2 t) payload. An artist's impression of the craft is shown in Figure 1.9. It is intended that it will become part of the Ballistic Missile Defense System Test bed. Some of the early activities will be to demonstrate station-keeping and autonomous flight. It will be used for military and civilian activities including:

- weather and environmental monitoring;
- short and long range missile warning;
- surveillance;
- target acquisition.



**Figure 1.9** Artist's impression of Lockheed Martin High Altitude Airship [99]. Reproduced by permission of © Lockheed Martin

#### 1.5.10.1 Discussion

This programme is one of the more credible developing HAPs. Lockheed Martin has significant experience; the development site at Akron has been developing lighter

than air vehicles since 1928. Being funded from the US military budget also provides further security that there will be significant financial resources to ensure that the craft will be built. However, there have been recent rumours that in order to keep to the tight development timescales the specification of the craft has been loosened, including providing a much reduced payload of 250 kg.

### *1.5.11 Advanced Technologies Group (ATG)*

In the early 2000s ATG was active in its Stratsat programme. Stratsat was a solar powered airship-based platform. However, ATG has since gone bankrupt and its technical team is in the process of reforming to pursue its many airship interests. They had some unique technology and deployment methods for their craft. Although it was proposed to power the craft using solar power, in conjunction with regenerative fuel cells/batteries for much of the time, they have also incorporated a diesel engine into some of their designs, which can be operated for limited periods to keep the craft on station in the event of wind gusts. The craft was designed for a 5 year mission and sufficient diesel will be taken on board for the full length of the mission. They have thought about the launch phase of the Stratsat, and ways to overcome the sheer size of such vehicles (up to 200 m long). They intended to launch the craft vertically out of the hangar in such a manner that it is outdoors and close to the ground for only a minimum period of time [100]. They had test facilities and hangars capable of housing such vehicles in Cardington, UK.

They have spent significant effort in pursuing Stratsat Malaysia, a project to be funded by the Malaysian government, which had BT and EADS as partners. They have been looking at a range of applications:

- Mobile Telephony;
- Civil Broadband;
- Civil Communications;
- Maritime Communications;
- Military Communications, Data Transmission and Surveillance;
- EOIR Imagery;
- Radar Imagery;
- Civil Tracking/Road Usage.

### *1.5.12 European Space Agency (ESA) Activity*

ESA has studied broadband delivery from HAPs, as part of its long-term low-level investigations into HAPs. This collaboration was between Airobotics GmbH (Germany), Booz Allen and Hamilton (Netherlands), University of Surrey (UK),



Politecnico di Torino (Italy), Fraunhofer Institute (Germany) and the German Aerospace Center (DLR) [23]. The remit of the study was to examine both the aeronautics and applications. Four categories of platform were compared:

- aerodynamic, solar powered;
- aerodynamic, fuel powered;
- aerostatic, solar powered;
- aerostatic, fuel powered.

Emphasis was placed on the use of solar power, but it was found that the eventual choice of platform depended heavily on the choice of payload, and the conceptual design for a platform has been developed.

The feasibility of a range of communications applications, including broadband, 3G, and DAB/DVB-T broadcasting have been studied. The choice of these payloads was based on technical feasibility, benefits for operators and market demands. The payloads themselves were based on three technical strategies: transparent; radio frequency switching; and regenerative.

This activity carries on from earlier ESA HALE study [22] which was completed a few years ago.

#### *1.5.13 Flemish Institute for Technological Research (VITO)*

One of the most interesting activities has been the development of the Zephyr which is a small stratospheric UAV. The Flemish Institute for Technological Research (VITO) has its ongoing Pegasus project [101] that is using a modified version of the Zephyr craft developed by QinetiQ [102] called the Mercator, and plans to deliver real-time remote sensing type applications, via a high speed communications link. The project timeline extends to 2011, by which time they hope to have a fully fledged remote sensing system operating.

#### *1.5.14 QinetiQ Ltd*

QinetiQ Ltd based in the UK has a number of disparate interests in HAPs, stemming from the days when it was the UK's Defence Research and Evaluation Agency (DERA). It has the following activities:

- Zephyr 3 unmanned plane and other UAV activity;
- airships;
- communications;
- surveillance/remote sensing.

### 1.5.15 *Space Data Corporation*

Space Data Corporation [103] is a US company that delivers wireless data services to rural and remote areas. One such example is the provision of telemetry services to the oil and gas industries. It is currently doing this using free flying balloon-based technology, their SkySite® network. These balloons are launched every 8–12 h from sites close to the coverage area, with the payload recovered on landing after around 24 h. They operate up to a height of 80 000–100 000 ft and provide at that altitude a coverage area of 350 miles (approximately 580 km) in diameter. Coverage is currently restricted to Texas, Oklahoma and Louisiana with limited coverage in neighbouring US states.

They can offer for example:

- SCADA communications;
- RTU/EFM/PLC monitoring;
- pump-off controller monitoring;
- kW meter reading;
- compressor/tank alarming;
- pipeline monitoring.

These operate in the 900 MHz band where Space Data holds a 1.7 MHz allocation of spectrum in the US. The company additionally offers services to the transportation sector, field communications and location services.

### 1.5.16 *HeliNet*

One of the early HAP projects was HeliNet (IST-1999-11214) [26, 27], which ran between January 2000 and March 2003 funded by the European Commission's FP5 programme. The project examined aeronautical issues and three prototype applications: broadband telecommunications; environmental monitoring; and vehicle localisation. A design for a scale size prototype stratospheric aircraft, 'Heliplat', was developed and key components built.

The University of York (UK) undertook the majority of the work in the broadband application, with input from Politecnico di Torino (Italy - also overall coordinator), Jožef Stefan Institute (Slovenia), the Budapest University of Technology and Economics (Hungary), and the Technical University of Catalonia (Spain). Barclay Associates (run by Professor Les Barclay, a former Deputy Director of the UK Radio Communications Agency) provided input on regulatory matters. Other members of the consortium were: CASA (Spain); Enigma Technology (UK); Carlo Gavazzi Space (Italy); Fastcom (Switzerland); and Ecole Polytechnique Federale de Lausanne (Switzerland).

### 1.5.17 *Lindstrand Technologies Ltd (UK)/University of Stuttgart*

Lindstrand Technologies Ltd [24], a UK company led by Per Lindstrand, has been involved in a project funded by the Koeber Institute and ESA. Lindstrand has established LBL as a 50/50 partnership with DASA (Daimler Chrysler Aerospace). The company has significant expertise in advanced materials required for airship-based HAPs, and production facilities capable of manufacturing airship envelopes.

The University of Stuttgart and Lindstrand won the Körber prize in 1999 [25]. Professor Bernd Kröplin has significant experience of airships and the group has a number of innovative designs for HAP vehicles. Their knowledge of the aerodynamic properties of large airships is probably the best in Europe.

### 1.5.18 *SkyStation*

This project was responsible for much of the initial work on the radio regulations within ITU-R. It is no longer active.

### 1.5.19 *Angel Technologies – HALO*

Angel Technologies [1, 21] developed a manned stratospheric plane in the late 1990s. It was planning to deliver continuous services to users using a fleet of these craft that would have a mission duration of 8 h, where they would circle above the coverage area. The project is not thought to be currently active, and was almost certainly a casualty of the dot.com boom and bust. One of the main reasons for inactivity could be down to the fact that the business model was not appropriate to the type of HAP vehicle. Such a vehicle may be much better suited to short-range missions, such as event servicing and disaster relief.

## References

1. G. M. Djuknic, J. Freidenfelds and Y. Okunev, *Establishing Wireless Communications Services via High-Altitude Aeronautical Platforms: A Concept Whose Time Has Come?* IEEE Commun. Mag., September 1997, pp. 128–135.
2. T. C. Tozer and D. Grace, *High-Altitude Platforms for Wireless Communications*, IEE Electron. Commun. Eng. J., June 2001, pp. 127–137.
3. D. Grace, N. E. Daly, T. C. Tozer, A. G. Burr and D. A. J. Pearce, *Providing Multimedia Communications from High Altitude Platforms*, Int. J. Sat. Commun., November 2001, No. 19, pp. 559–580.
4. Grob, G520T, Egrett Platform, [www.globalsecurity.org/military/world/europe/egrett.htm](http://www.globalsecurity.org/military/world/europe/egrett.htm), January 2008.
5. Grob G520T Egrett Platform on Grob Website, [www.grob-aerospace.net/index.php?id=137](http://www.grob-aerospace.net/index.php?id=137), January 2008.

6. AeroVironment launches Global Observer Program for the US Special Operations Command, [www.defense-update.com/newscast/0907/news/260907\\_hale\\_av.htm](http://www.defense-update.com/newscast/0907/news/260907_hale_av.htm), 26 September 2007.
7. NASA Pathfinder Plus Platform, [www.dfrc.nasa.gov/gallery/photo/Pathfinder-Plus/index.html](http://www.dfrc.nasa.gov/gallery/photo/Pathfinder-Plus/index.html), January 2008.
8. Lockheed Martin High Altitude Airship, [www.globalsecurity.org/intell/systems/haa.htm](http://www.globalsecurity.org/intell/systems/haa.htm), January 2008.
9. Lockheed Martin HAA Program, [www.lockheedmartin.com/products/HighAltitudeAirship/index.html](http://www.lockheedmartin.com/products/HighAltitudeAirship/index.html), January 2008.
10. Global Hawk Platform, [www.globalsecurity.org/intell/systems/global\\_hawk.htm](http://www.globalsecurity.org/intell/systems/global_hawk.htm), January 2008.
11. UAVNet Thematic Network, [www.uavnet.com](http://www.uavnet.com), January 2008.
12. D. Grace, *et al.*, *Applications and Business Models for HAP Delivery*, FP6 CAPANINA Project, Doc Ref: CAP-D26-W10-BUT-PUB-01 [www.capanina.org/documents/CAP-D26-WP11-BT-PUB-01.pdf](http://www.capanina.org/documents/CAP-D26-WP11-BT-PUB-01.pdf), January 2007.
13. ITU Recommendation ITU-R F.1500, *Preferred Characteristics of Systems in the Fixed Service Using High Altitude Platforms Operating in the Bands 47.2-47.5 GHz and 47.9-48.2 GHz*, International Telecommunications Union, Geneva, Switzerland, 2000.
14. ITU Recommendation ITU-R F.1569, *Technical and Operational Characteristics for the Fixed Service Using High Altitude Platform Stations in the Bands 27.5-28.35 GHz and 31-31.3 GHz*, International Telecommunications Union, Geneva, Switzerland, 2002.
15. ITU Recommendation M.1456, *Minimum Performance Characteristics and Operational Conditions for HAPS Providing IMT-2000 in the Bands 1885-1980 MHz, 2010-2025 MHz and 2110-2170 MHz in Regions 1 and 3 and 1885-1980 MHz and 2110-2160 MHz in Region 2*, International Telecommunications Union, Geneva, Switzerland, 2000.
16. F. Dovis, R. Fantini, M. Mondin and P. Savi, *Small-Scale Fading for High-Altitude Platform (HAP) Propagation Channels*, IEEE J. Selected Areas Commun., April 2002, Vol. 20, No. 3, pp. 641–647.
17. E. Falletti, M. Mondin, F. Dovis and D. Grace, *Integration of a HAP within a Terrestrial UMTS Network: Interference Analysis and Cell Dimensioning*, Int. J. Wireless Personal Communications - Special Issue on Broadband Mobile Terrestrial-Satellite Integrated Systems, February 2003, Vol. 24, No. 2.
18. S. Masumura and M. Nakagawa, *Joint System of Terrestrial and High Altitude Platform Stations (HAPS) Cellular for W-CDMA Mobile Communications*, IEICE Trans. Commun., October 2002, Vol. E85-B, No. 10, pp. 2051–2058.
19. M. Oodo, R. Miura, T. Hori, T. Morisaki, K. Kashiki and M. Suzuki, *Sharing and Compatibility Study Between Fixed Service Using High Altitude Platform Stations (HAPS) and Other Services in 31/28 GHz Bands*, Wireless Personal Communications, 2002, Vol. 23, pp. 3–14.
20. R. Steele, *Guest editorial - An Update on Personal Communications*, IEEE Commun. Mag., December 1992, pp. 30–31.
21. N. J. Collela, J. N. Martin and I.F. Akyildiz, *The HALO Network*, IEEE Commun. Mag., June 2000, pp. 142–148.
22. ESA HALE Study, [www.lindstrand.co.uk/hale.html](http://www.lindstrand.co.uk/hale.html).
23. Stratospheric Platforms - a definition study for an ESA system, European Space Agency, April 2004, [telecom.esa.int/telecom/www/object/index.cfm?fobjectid=8188](http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=8188).
24. Lindstrand Technologies Website, [www.hiflyer.com](http://www.hiflyer.com).
25. *Körber Prize Winner 1999 - High-Altitude Platforms to Supplement Satellites*, [www.koerber-stiftung.de/english/publications/press\\_archive/pm\\_1999/pm\\_12\\_07\\_99.html](http://www.koerber-stiftung.de/english/publications/press_archive/pm_1999/pm_12_07_99.html).
26. J. Thornton, D. Grace, M. H. Capstick and T. C. Tozer, *Optimising an Array of Antennas for Cellular Coverage from a High Altitude Platform*, IEEE Trans. Wireless Commun., May 2003, Vol. 2, No. 3, pp. 484–492.
27. D. Grace, J. Thornton, T. Konefal, C. Spillard and T. C. Tozer, *Broadband Communications from High Altitude Platforms - The HeliNet Solution*, Invited Paper for Wireless Personal Mobile Conference, Aalborg, Denmark, September 2001, Vol. 1, pp. 75–80.
28. D. Grace, M. Mohorčić, M. H. Capstick, M. Bobbio Pallavicini and M. Fitch, *Integrating Users into the Wider Broadband Network via High Altitude Platforms*, IEEE Wireless Commun., October 2005, Vol. 12, No. 5, pp. 98–105.

29. CAPANINA Website, [www.capanina.org](http://www.capanina.org).
30. AV Inc Website, [www.av-inc.com](http://www.av-inc.com).
31. T. E. Noll, J. M. Brown, M. E. Perez-Davis, S. D. Ishmael, G. C. Tiffany and M. Gaier, *Investigation of the Helios Prototype Aircraft Mishap*, Vol. I Mishap Report, NASA, January 2004, [www.nasa.gov/pdf/64317main\\_helios.pdf](http://www.nasa.gov/pdf/64317main_helios.pdf).
32. S. Konyavko, *HAA and Lighter than Air Development in the US*, International HAPS Workshop, Seoul, Korea, Korean Institute of Industrial Engineers, and Electronics and Telecommunications Research Institute, November 2004.
33. StratXX AG Website, [www.stratxx.com](http://www.stratxx.com).
34. ERS srl Website, [www.ers-srl.com](http://www.ers-srl.com).
35. COST297 Website, [www.hapcos.org](http://www.hapcos.org).
36. Z. Peng and D. Grace, *Coexistence Performance of High Altitude Platform and Terrestrial Systems Using Gigabit Communication Links to Serve Specialist Users*, EURASIP J. Wireless Commun. Network – Special Issue: Advanced Communication Techniques and Applications for High Altitude Platforms, October 2008, Vol. 2008, article ID 892512, 11 pages, 2008. doi: 10.1155/2008/892512.
37. D. Grace, J. Thornton, G. Chen, G. P. White and T. C. Tozer, *Improving the System Capacity of Broadband Services Using Multiple High Altitude Platforms*, IEEE Trans. Wireless Commun., March 2005, Vol. 4, No. 2, pp. 700–709.
38. ERS srl Website, [www.ers-srl.com](http://www.ers-srl.com), January 2008.
39. D. Grace, N. E. Daly, T. C. Tozer, A. G. Burr and D. A. J. Pearce, *Providing Multimedia Communications Services from High Altitude Platforms*, Int. J. Satellite Commun., November 2001, Vol. 19, No. 19, pp. 559–580.
40. T. Konefal, C. Spillard and D. Grace, *Site Diversity for High Altitude Platforms: A Method for the Prediction of Joint Site Attenuation Statistics*, IEE Proc. Ant. Prop., April 2002, Vol. 149, No. 2, pp. 124–128.
41. E. Falletti, F. Sellone, C. L. Spillard and D. Grace, *A Transmit and Receive Multi-Antenna Channel Model and Simulator for Communications from High Altitude Platforms*, Int. J. Wireless Information Networks, January 2006, Vol. 13, No. 1, pp. 59–75.
42. Iskandar and S. Shimamoto, *Channel Characterization and Performance Evaluation of Mobile Communication Employing Stratospheric Platforms*, IEICE Trans. Commun., March 2006, Vol. E89-B, No. 3.
43. T. Celcer, G. Kandus, T. Javornik, M. H. Capstick and M. Mohorčič, *Analysis of HAP Propagation Channel Measurement Data*, Proc. 15th IST Mobile and Wireless Communications Summit 2006, Myconos, Greece, 4–8 June 2006.
44. Resolution 734 (Rev. WRC-07), *Studies for Spectrum Identification for Gateway Links for High Altitude Platform Stations in the Range from 5850 to 7250 MHz*, World Radiocommunication Conference, Geneva, 2007.
45. International Telecommunications Union Website, [www.itu.int](http://www.itu.int).
46. *USEHAAS Strategic Research Agenda – Developing a EU Research Strategy in the High Altitude Aircraft (HAAS) Sector – Volume 1*, Technical Report, FP6 USEHAAS Specific Support Action, ASA4-CT-2005-516081, [www.usehaas.org](http://www.usehaas.org).
47. ASTRAEA Project Website, [www.projectastraea.co.uk](http://www.projectastraea.co.uk).
48. M. Mohorčič, T. Javornik, A. Lavric, I. Jelovcan, E. Falletti, M. Mondin, A. Boch, L. Feletti, L. Lo Presti, D. Merino, D. Borio, J. A. Delgado Penin, F. Arino and E. Bertran, *Selection of Broadband Communication Standard for High-Speed Mobile Scenario*, FP6 CAPANINA Project, Doc Ref: CAP-D09-WP21-JSI-PUB-01, [www.capanina.org/documents/CAP-D09-WP21-JSI-PUB-01.pdf](http://www.capanina.org/documents/CAP-D09-WP21-JSI-PUB-01.pdf), January 2005.
49. Y. C. Foo, W. L. Lim and R. Tafazolli, *Performance of High Altitude Platform Station (HAPS) in Delivery of IMT-2000 W-CDMA*, Proc. Stratospheric Platform Systems Workshop (SPSW 2000), Tokyo, Japan, September 2000.
50. B. El-Jabu and R. Steele, *Cellular Communications Using Aerial Platforms*, IEEE Trans. Vehicular Technol., May 2001, Vol. 50, No. 3, pp. 686–700.
51. E. Falletti, M. Mondin, F. Dovis and D. Grace, *Integration of a HAP within a Terrestrial UMTS Network: Interference Analysis and Cell Dimensioning*, Wireless Personal Communications, February 2003, Vol. 24, No. 2, pp. 291–325.

52. D. I. Axiotis, M. E. Theologou and E. D. Sykas, *The Effect of Platform Instability on the System Level Performance of HAPS UMTS*, IEEE Commun. Lett., February 2004, Vol. 8, No. 2, pp. 111–113.
53. T. Hult, D. Grace and A. Mohammed, *WCDMA Uplink Interference Assessment from Multiple High Altitude Platform Configurations*, EURASIP J. Wireless Commun. Networking, 2008, Vol. 2008, Article ID 182042, 10.1155/2008/182042.
54. T. V. Do, N. H. Do and R. Chakka, *Performance Evaluation of the High Speed Downlink Packet Access in Communications Networks Based on High Altitude Platforms*, Lecture Notes in Computer Science 5055, Springer, 2008, pp. 310–322.
55. B. Taha-Ahmed and M. Calvo-Ramón, *UMTS-HSDPA in High Altitude Platforms (HAPs) Communications with Finite Transmitted Power and Unequal Cell's Load*, Computer Commun., March 2009, Vol. 32, Issue 5, pp. 828–833.
56. M. Pent, L. Lo Presti, M. Mondin and S. Orsi, *HELIPLAT as a GSM base station: a feasibility study*, Proc. Data System in Aerospace (DASIA 99), Lisbon, Portugal, 17–21 May 1999.
57. F. Dovis and F. Sellone, *Smart Antenna System Design for Airborne GSM Base-Stations*, Proc. 2000 IEEE Sensor Array and Multichannel Signal Processing Workshop, Cambridge, UK, 16–17 March 2000, pp. 429–433.
58. M. Mondin, F. Dovis and P. Mulassano, *On the Use of HALE Platforms as GSM Base Stations*, IEEE Personal Commun., April 2001, Vol. 8, No. 2, pp. 37–44.
59. M. Bobbio Pallavicini, F. Dovis, E. Magli and P. Mulassano, *HeliNet Project: the Current Status and the Road Ahead*, Proc. Data Systems in Aerospace (DASIA 2001), Nice, France, May 2001.
60. J. Thornton, D. Grace, C. Spillard, T. Konefal and T. C. Tozer, *Broadband Communications from a High-Altitude Platform: the European HeliNet Programme*, Electron Commun. Eng. J., June 2001, pp. 138–144.
61. D. Martín-Sacristán, J. F. Monserrat, J. Cabrejas-Peñuelas, D. Calabuig, S. Garrigas and N. Cardona, *On the Way Towards Fourth-Generation Mobile: 3GPP LTE and LTE-Advanced*, EURASIP J. Wireless Commun. Networking, 2009, Vol. 2009, Article ID 354089, 10.1155/2009/354089.
62. R. Prasad and A. Mihovska (Eds), *New Horizons in Mobile and Wireless Communications, Volume 2: Networks, Services, and Applications*, Artech House, 2009.
63. R. B. Marks, I. C. Gifford and B. O'Hara, *Standards in IEEE 802 Unleash the Wireless Internet*, Microwave Mag., June 2001, pp. 46–56.
64. IEEE 802 LAN/MAN Standards Committee Website, <http://grouper.ieee.org/groups/802/>.
65. The Wi-Fi Alliance Website, <http://www.wi-fi.org/>.
66. J. Thornton, A. D. White and T. C. Tozer, *WiMAX Payload for High Altitude Platform Experimental Trials*, EURASIP J. Wireless Commun. Networking, 2008, Vol. 2008, Article ID 498517, 10.1155/2008/498517.
67. C. Eklund, R. B. Marks, K. L. Stanwood and S. Wang, *IEEE Standard 802.16: A Technical Overview of the Wireless MAN Air Interface for Broadband Wireless Access*, IEEE Commun. Mag., June 2002, pp. 98–107.
68. The WiMAX Forum Website, <http://www.wimaxforum.org/>.
69. ETSI EN 300 421 V1.1.2 (1997-08), *European Standard (Telecommunications Series), Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for 11/12 GHz Satellite Services*
70. ETSI EN 302 307 V1.1.1 (2004-06), *European Standard (Telecommunications series), Digital Video Broadcasting (DVB); Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications*
71. ETSI EN 301 790 V1.3.1 (2003-03), *European Standard (Telecommunications Series), Digital Video Broadcasting (DVB); Interaction Channel For Satellite Distribution Systems*
72. E. Cianca, M. De Sanctis, A. De Luise, M. Antonini, D. Teotino, M. Ruggieri and R. Prasad, *Integrated Satellite-HAP Systems*, IEEE Radio Commun., December 2005, pp. S33–S39.
73. F. De Rango, M. Tropea and S. Marano, *Integrated Services on High Altitude Platform: Receiver Driven Smart Selection of HAP-Geo Satellite Wireless Access Segment and Performance Evaluation*, Int. J. Wireless Inform. Networks, January 2006, Vol. 13, No. 1, pp. 77–94.

74. B. Bennett, K. Quock, E. Summers, M. Difrancisco and B. A. Hamilton, *DVB-S2 Technology Development for DoDIP SATCOM*, Proc. Military Communications Conference (MILCOM 2006), Washington, DC, USA, 23–25 October 2006.
75. M. Smolnikar, M. Mohorčič and T. Javornik, *Utilisation of LDPC Decoder Parameters in DVB-S2 ACM Procedures*, Proc. 2007 International Workshop on Satellite and Space Communication (IWSSC'07), Salzburg, Austria, 12–14 September 2007, pp. 194–198.
76. M. Smolnikar, A. Aroumont, M. Mohorčič, T. Javornik and L. Castanet, *On Transmission Modes Subset Selection in DVB-S2/RCS Satellite Systems*, Proc. 2008 International Workshop on Satellite and Space Communications (IWSSC'08), Toulouse, France, 1–3 October 2008, pp. 263–267.
77. M. Smolnikar, T. Javornik and M. Mohorčič, *Target BER Driven Adaptive Coding and Modulation in HAP Based DVB-S2 System*, Proc. 4th Advanced Satellite Mobile Systems (ASMS'08), Bologna, Italy, 25–28 August 2008.
78. M. Mohorčič, M. Smolnikar and T. Javornik, *Performance Comparison of Adaptive Coding and Modulation in HAP Based IEEE 802.16 and DVB-S2 Systems*, Proc. 26th AIAA International Communications Satellite Systems (ICSSC'08), San Diego, CA, USA, 10–12 June 2008.
79. M. Smolnikar, T. Javornik, M. Mohorčič and M. Berioli, *DVB-S2 Adaptive Coding and Modulation for HAP Communication System*, Proc. 2008 IEEE 67th Vehicular Technology Conference (VTC2008-spring), Marina Bay, Singapore, 11–14 May 2008, pp. 2947–2951.
80. M. Bobbio Pallavcini, B. Cahill, J. Horwath and M. Capstick *Test Results Summary Report - Part 1*, FP6 CAPANINA Project, Doc Ref: CAP-D22a-W40-CGS-PUB-01, [www.capanina.org/documents/CAP-D22a-WP44-CGS-PUB-01.pdf](http://www.capanina.org/documents/CAP-D22a-WP44-CGS-PUB-01.pdf), September 2006.
81. J. Horwath, *Final Optical Terminal Design Report*, CAPANINA Project, Doc Ref: CAP-D21-WP34-DLR-PUB-01, [www.capanina.org/documents/CAP-D21-WP34-DLR-PUB-01.pdf](http://www.capanina.org/documents/CAP-D21-WP34-DLR-PUB-01.pdf), August 2006.
82. M. Bobbio Pallavcini, *Test Results Summary Report - Part 2*, FP6 CAPANINA Project, Doc Ref: CAP-D22b-W40-CGS-PUB-01, [www.capanina.org/documents/CAP-D22b-WP44-CGS-PUB-01.pdf](http://www.capanina.org/documents/CAP-D22b-WP44-CGS-PUB-01.pdf), January 2007.
83. USEHAAS Website, [www.usehaas.org](http://www.usehaas.org).
84. R. Miura and M. Suzuki, *R&D Achievements and Future Perspective on Telecommunications and Broadcasting System Using Stratospheric Platform*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
85. K. Ohasi, *Promising Features of the Integrated SPF Tracking and Control System*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
86. M. Oodo, H. Tsuji, R. Miura, M. Maruyama and M. Suzuki, *Experiment of IMT-2000 Using Stratospheric-Flying Solar-Powered Airplane*, GLOBECOM 2003 - IEEE Global Telecommunications Conference, December 2003, Vol. 22, No. 1, pp. 1152–1156.
87. M. Nagatsuka, Y. Morishita, M. Suzuki and R. Miura, *Testing of Digital Television Broadcasting from the Stratosphere*, IEEE Trans. Broadcasting, December 2004, Vol. 50, No. 4.
88. Y. Arakaki, R. Miura, M. Oodo, Y. Morishita and M. Suzuki, *Preliminary Flight Tests for Stratospheric Platform Systems - mm-Wave Multi-Beam Hone (MBH) Antenna Systems Using Helicopter*, AIAA-2003-2270 21st International Communications Satellite Systems Conference and Exhibit, Yokohama, Japan, 15–19 April 2003.
89. M. Nagatsuka et al., *Experiment for Wide-Area Digital Broadcasting*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
90. H. Tsuji et al., *Fundamental Experiment of Real-Time Estimation of Mobile-Terminal Localization*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
91. Y. Arimoto et al., *Laser Tracking Trial between the Airship and Ground Station*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
92. Article 5, Radio Regulation, ITU, 2004 Edition.
93. D.-S. Ahn, B.-J. Ku, T. C. Hong, J. M. Park, B.-S. Kang and Y.-S. Kim, *Core Technology Development and Standardization for HAPS in Korea*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).

94. [www.kari.go.kr](http://www.kari.go.kr).
95. D.-S. Ahn, B.-J. Ku, T. C. Hong, J. M. Park, B.-S. Kang and Y.-S. Kim, *Core Technology Development and Standardization for HAPS in Korea*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
96. J.-M. Park, B.-J. Ku, Y. S. Kim and D.-S. Ahn, *Technology Development for Wireless Communications System Using Stratospheric Platform in Korea*, PIMRC 2002, Lisbon, Portugal, September 2002, pp. 162–170.
97. Preliminary Draft New Recommendation ITU-R F.[HAPS-RRS], *Methodology to Evaluate Interference from Fixed Service System Using High Altitude Platform Stations (HAPS) To Radio-Relay System in the Bands above 3 GHz*, October 2004.
98. J. Del Frate, *Developing Technologies for High Altitude Platforms and Long Endurance*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005 (in Japanese/English).
99. Lockheed Martin High Altitude Airship, [www.lockheedmartin.com/data/assets/7966.pdf](http://www.lockheedmartin.com/data/assets/7966.pdf).
100. J. Miller, *STRATSAT ATG Progress Update 2005*, 5th Stratospheric Platforms Systems Workshop, Tokyo, Japan, February 2005. (in Japanese/English).
101. Pegasus for Europe Website, [www.pegasus4europe.com](http://www.pegasus4europe.com).
102. QinetiQ Website, [www.qinetiq.com](http://www.qinetiq.com).
103. Space Data Corporation Website, [www.spacedata.net](http://www.spacedata.net).