Abstract

Radio makes it possible to have communication "without wires." This is a highly attractive proposition for mobile personal communications; it is increasingly an economic alternative to traditional wired phone systems, and is a potential technology for high-speed Internet access. But in the terrestrial environment, radio signals are subject to scattering and multipath effects that limit the quantity of information possible to transmit in a given bandwidth, as well as the distances over which it can be communicated. In cellular and personal communication systems (PCS), radio coverage is deliberately restricted further to allow for frequency reuse. As a consequence, terrestrial wireless networks comprise numerous antenna towers, base stations, wired or microwave links, and mobile switching centers, all dispersed over wide geographical areas. Satellites can provide wireless coverage with much less terestrial infrastructure, but only by introducing considerably problems of their own. Geosynchronous satellites require expensive and bulky user terminals and introduce large signal delay because of their great distance. Nongeosynchronous satellites, because of their motion with respect to points on the ground, greatly increase system complexity. Proposed high-altitude aeronautical platforms (HAAPs) are an intriguing alternative. From a communications perspective, they would have many advantages over both their terrestrial and satellite counterparts. If HAAPs prove to be reasonably stable, reliable, and not too costly, they will offerr considerable opportunities for wireless services provision, and introduction of innovative communications concepts such as cell scanning and stratospheric radio relays.

Establishing Wireless Communications Services via High-Altitude Aeronautical Platforms: A Concept Whose Time Has Come?

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There are two well-established methods for providing wireless communication services: terrestrially based systems, as used in cellular and personal communications systems (PCS), and satellites. Each concept has its specific advantages and disadvantages. The high-altitude aeronautical platform (HAAP) technology, we will argue, would have many of the advantages of both terrestrial and satellite systems, while at the same time avoiding many of their pitfalls. Also, it would bring advantages of its own, not available in current systems. Table 1 summarizes key points that will be made in this discussion, concerning terrestrial systems, and mobile satellite systems based on geosynchronous Earth orbit (GEO), low-altitude Earth orbit (LEO), and medium-altitude Earth orbit (MEO) satellites.

High Altitude Aeronautical Platforms

Active and passive communications platforms at high altitudes are not a new idea — before the 1962 Telstar satellite, long distance telephone calls were made by bouncing signals from the Echo, a giant balloon launched in 1960 to passively reflect broadcasts from the Bell Laboratories facility at Crawford Hill. The focus of this article is airborne platforms — airships, planes, helicopters, or some hybrid solutions — which could operate at stratospheric altitudes for significant periods of time, be low-cost, and be capable of carrying sizable, multipurpose communications payloads. Of particular interest are ways to implement cellular/PCS or high-speed data networks using technological developments in airborne platforms which raise the potential for combining the advantages of geostationarity with terrestrial-systems-like coverage and signal delay. Data from worldwide measurements of stratospheric wind velocities indicate that their minimum, averaging 30 to 40 m/s, occurs between 65,000 and 75,000 ft depending on latitude. These are long-term averages, and little is known about time scales on the order of minutes or hours. This is the basis for the most often stated critique of airborne platforms, namely that they will not be able to withstand sudden wind gusts, resulting in a temporary or total loss of communication. The instantaneous power, P, needed to counter the wind force exerted on an airship is

$$P = 1/2\rho C_d S_c v^3$$

where ρ is the air density (which at stratospheric altitudes is only a few percent of the density at sea level,) C_d is the drag coefficient, S_c is the airship cross-sectional area, and v is the instantaneous wind velocity. The wind direction in this layer remains steady for most of the year, except for a twice yearly change of 180°. Typical wind velocity profiles obtained by the High Resolution Doppler Imager (HRDI) on the National Aeronautics and Space Administration's (NASA's) Upper Atmospheric Research Satellite (UARS) can be seen at http://www.sprl.umich.edu/HRDI/hrdi_homepage.html.

Platform designs in the heavier-than-air class benefited from recent advances in the development of composite materials; computers and navigational systems; low-speed, high-

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

Table 1. *Summary comparison of wireless systems.*

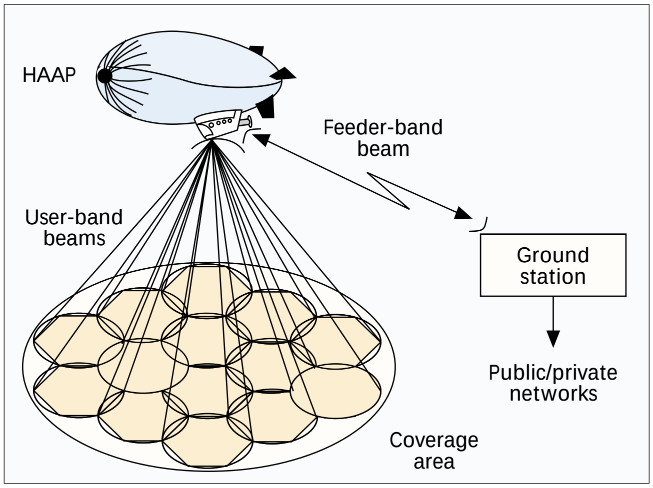

Figure 1. *General HAAP-based system layout.*

altitude aerodynamics; propulsion systems, including internal combustion and solar-powered; and the exceptional interest of the military in unmanned aerial vehicles (UAVs). The goal of the Defense Advanced Research Projects Agency's (DARPA's) Airborne Communications Node (ACN) program is to develop a 900-lb communications payload for a UAV having 42-hr endurance at altitudes above 60,000 ft.[1] General Atomics Aeronautical Systems (San Diego, California) has already developed several UAVs, and it is likely that this program will be the first to demonstrate the airborne-platform communications concept [5]. More information on related projects can be found by following the links from the European Space Agency (ESA) Web page on high-altitude long endurance (HALE) platforms, at http://www.estec.esa.nl/halewww/www/hale.htm.

An early design from Jet Propulsion Laboratories (JPL) involved the use of pilotless planes circling above the coverage area for weeks or months without landing, powered by microwave beams from the ground. This approach draws on wireless power transmission research in the space-station context, but the problems are in transmission efficiency, ground-station cost, safety of flying drones over populated areas, and danger to other aircraft from high-power microwave radiation. Some current approaches involve piloted and conventionally powered lightweight planes in a holding pattern at 70,000 feet, but their time aloft would be limited to about 8 hours due to fuel constraints and human factors.

In the lighter-than-air arena, Skysat Communications Network Corporation (New York) recently came with a plan for regional telecommunications services over an area up to 600 mi in diameter, using airship-based communications platforms positioned at 70,000 ft. The airships, a patented design by Av-Intel Inc. from Canada, are unmanned, neutrally buoyant, and conventionally powered dirigibles. The engines will have to be of special construction because of low air pressure at the planned altitude. They will be 975 ft long and 150 ft in diameter, have a maximum cruise speed of 56 knots, and be able to carry up to 2000 lbs of communications payload. These airships will be capable of staying aloft for several months, but actual flight duration will mostly depend on the wind speeds at a particular location.

The most ambitious plan so far has been developed by Sky Station International Inc. (http://www.skystation.com), which intends to place a network of 250 stratospheric stations in fixed positions 100,000 ft above Earth, supported by several thousand ground control and switching centers [1]. The network could serve many millions of small and inexpensive fixed, portable, and mobile communications terminals for Internet access and video telephony service. Stations in the form of 30-ton helium-filled dirigibles will be maintained in correct position using the Global Positioning System (GPS). Solar panels integrated into the dirigible skin will supply power to Corona Ion Engines (needed to counter stratospheric winds and keep dirigibles in place). Frequency bands proposed for use are 47.2 to 47.5 GHz (uplink) and 47.9 to 48.2 GHz (downlink), and Sky Station Inc. has applied for international spectrum allocation in this band. The payload will consist of a beamforming phased array antenna, and a bank of regenerative processors for transmission/reception, modulation/demodulation, encoding/decoding, multiplexing/demultiplexing, and switching functions.

The RotoStar concept developed by Silver Arrow (Israel) also

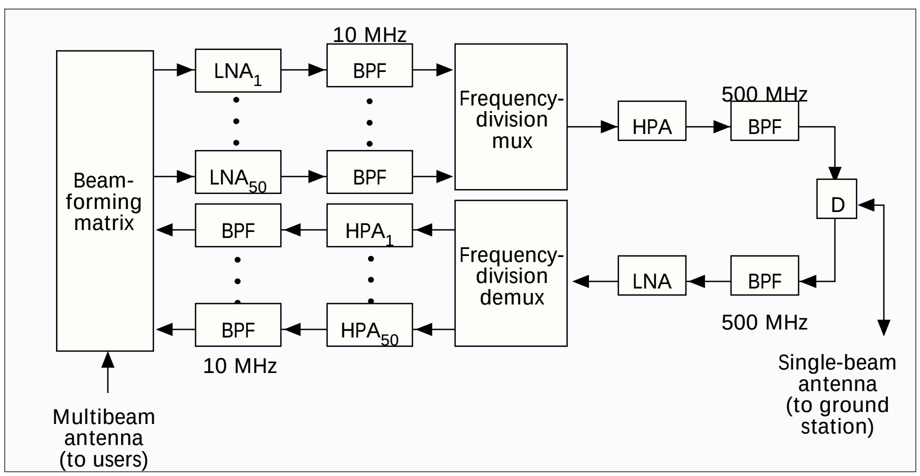

Figure 2. *Airborne platform payload equipment in a CDMA system.*

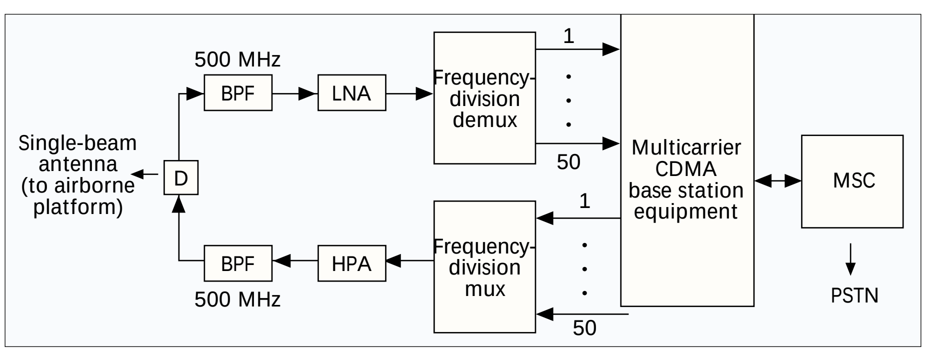

Figure 3. *Ground equipment in a HAAP-based CDMA system.*

[1] *Descriptions of the program are at ISX Corporation and DARPA Web pages, maco.dc.isx.com/iso/battle/airborne.html and www.darpa.mil/documents/procure97/iso.html, respectively.*

involves an unmanned dirigible orbiting at 70,000 ft, but with helicopter-like "smart wings" (http://www.weizmann.ac.il/consolar/spsp.html). Conventionally powered RotoStars would be able to stay aloft for four days, and internal combustion engines are currently under development; solar-powered platforms would endure many months on station, but their engines still require a technological breakthrough to be implemented.

Finally, researchers from the University of California at Los Angeles and Rockwell Corporation, in partnership with NASA, are developing a prototype for a fleet of solar-powered autonomous aircraft which would fly at high altitudes in a geese-like V-formation. And in Japan, the Ministry of Posts and Telecommunications has conducted a study on teaming up with the private sector and universities to develop a mobile phone network covering the entire Japanese archipelago, based on 20 solar and/or fuel-cell-powered airships positioned at 20-km altitude.

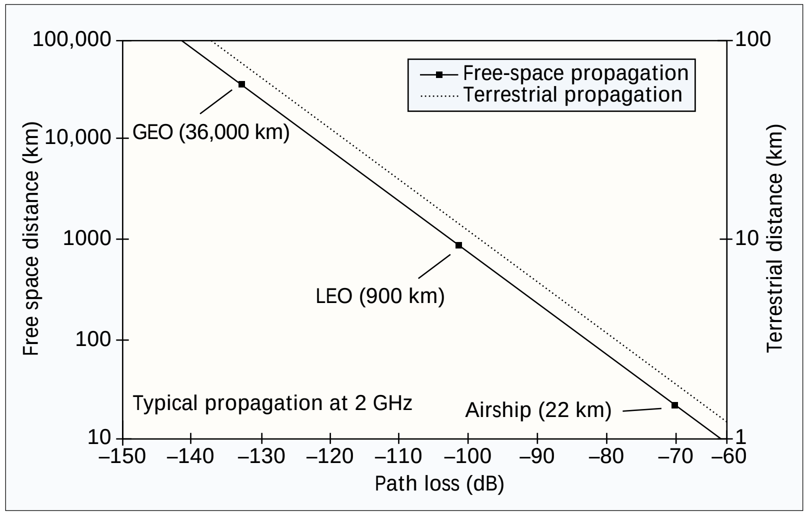

Figure 4. *Attenuation in free-space and terrestrial-type propagation.*

The choice of energy source is of fundamental importance. Fossil fuel is heavy, and therefore expensive to lift and maintain at altitude. The very large size of a lighter-than-air HAAP using fossil fuel, for example, is dtermined by the need to lift the fuel that will keep it in place — proponents have suggested designs that would operate for anywhere from a few days to a few months between refueling. Solar energy has considerable appeal, particularly if we assume that, for either buoyancy or aerodynamic lift in the thin atmosphere, the HAAP will contain large surfaces suitable for collectors. Up to 1300 W/m^2 are available at the equator, which is quite substantial even if we assume solar cell efficiencies of 10–15 percent. The problem is that energy has to be stored for overnight use. Adding batteries, such as lithium-ion at about 110 W hr/kg, makes for a very large (and expensive) HAAP.

System Architecture and Parameters

General Architecture

A typical HAAP-based communications system structure is shown in Fig. 1. The platform is positioned above the coverage area. Lighter-than-air HAAPs are kept stationary, while airplane-based HAAPs are flown in a tight circle. For broadcast applications, a simple antenna beams signals to terminals on the ground. For individualized communications, such as telephony, "cells" are created on the ground by some beamforming technique in order to reuse channels for spatially separated users, as is done in cellular service. Beamforming can be as sophisticated as the use of phased-array antennas, or as straightforward as the use of lightweight, possible inflatable parabolic dishes with mechanical steering. In the case of a moving HAAP it would also be necessary to compensate motion by electronic or mechanical means in order to keep the cells stationary, or to "hand off" connections between cells as is done in cellular telephony.

Onboard Equipment

Depending on the application, there are many ways in which a HAAP-based communications system could be implemented. A typical design would seek high reliability, low power consumption, and minimum weight and size for the onboard portion of the system. That would lead to an architecture which places most of the system on the ground, for example, by limiting airborne components to a multichannel transponder, user-beam and feeder-beam antennas, and associated antenna interfaces.

Fig. 2 shows a code-division multiple access (CDMA) system built around a standard satellite-like transponder bandwidth of 500 MHz. The transponder bandwidth can accommodate up to 50 antenna beams with 8 spread spectrum carriers/beam (assuming 1.25 MHz carrier bandwidth). Carrier signals coming from a ground cell (i.e., from a particular beam) and received by the onboard antenna are first amplified in low-noise amplifiers (LNAs). They are then limited to the standard 10 MHz bandwidth by band-pass filters (BPFs), and frequency-division multiplexed (muxed). Before transmission to the ground station, multiplexed signals are amplified in the high-power amplifier (HPA), BPFed to the transponder bandwidth, and passed through the diplexer (D). Signal path in the opposite direction is similar and includes an additional demultiplexing (demux) stage. If commercial off-the-shelf equipment is to be used onboard, it will have to be placed in a chamber with climate and air-pressure control to prevent freezing, overheating (due to reduced heat convection), and dielectric breakdown.

Ground Installations

Communications between the HAAP and the ground would typically be concentrated into a single ground installation, or perhaps into two locations for redundancy. There would be considerable advantage to collocating RF units, base stations, and mobile switching centers (MSCs).

The ground system in Fig. 3 corresponds to the onboard equipment from Fig. 2. Carrier signals coming from the airborne station are filtered by a BPF, amplified in LNAs, demultiplexed in the demux, and passed to CDMA base stations. It should be emphasized here that a base station in this case consists only of a radio channel frame, since there is no need for power-amplifier and antenna-interface frames for every base station; a common wideband power amplifier and an antenna will serve all the collocated base stations. From base stations, the signals are passed in the usual manner to the mobile MSC and public switched telephone network (PSTN). The return signal path toward the airborne station is similar, except for the inverse multiplexing operation in the mux and high-power amplification by the HPA.

HAAP-Based Communications System Performance

One of the most attractive features of an airborne platform-based wireless system is its very favorable path-loss characteristic relative to either terrestrial or satellite systems. In Fig. 4, a typical path loss vs. distance is shown for terrestrial and nonterrestrial systems. For nonterrestrial systems, we assume free-space path loss, inversely proportional to the square of the distance, $1/r^2$, or 20 dB/decade. In terrestrial systems path loss is a stochastic variable (often determined empirically,) and we take the most commonly assumed ratio, $1/r^4$, or 40 dB/decade [2]. The more favorable propagation characteristics in satellite systems are more than offset by their great distance. Even LEO distances cause path losses comparable to those in a relatively large terrestrial cell: path loss to a LEO satellite at 900 km altitude is equal to the path loss along the ground at 10 km distance. By contrast, from an airship at 22 km altitude to a point on the ground directly below it, path loss is the same as at the edge of a relatively small terrestrial-system cell with approximately 2 km radius.

In addition to free-space-like propagation, energy budget of the user link in an airborne-based system is further enhanced by Ricean, not Rayleigh type, fading and high-gain platform antennas. As a result, the system can operate with conventional cellular/PCS handsets and relatively simple onboard equipment. To show that power requirements for onboard equipment (of the full-fledged system example described in this section) are within limits of the onboard amplifier and power supply, we compare the transmitter powers of terrestrial and airborne systems. Consider the situation presented in Fig. 5, where the antenna tower of a terrestrial system is up to 150 ft in height, while HAAP is at an altitude of 12 to 15 mi. The maximum coverage radius, d_H, for airborne systems is approximately 75 mi to maintain the look angle, α, of at least 10°. The antenna gain in terrestrial systems is G_T = 10–17 dB, while the gain of an airborne antenna is G_H = 30–35 dB (we use capital G for antenna gain throughout, since the units will be obvious from the context).

In order for a terrestrial and a HAAP-based system to maintain the same quality of service, it is required that the signal-to-noise ratios (SNRs) be the same at the edge of their respective coverage areas. SNR in both cases is directly proportional to transmitter power P and antenna gain G, and inversely proportional to the power of distance R between transmitting and receiving antennas,

$$SNR \propto \frac{P \times G}{R^n}$$

The path loss exponent, n, has values from 2 to 5 [2]. For free-space propagation $n = 2$, in a suburban-type environment $n = 3.84$, and for highly urban areas the value is close to 5. This estimation obviously refers to the average SNR; taking fades into account gives additional gain for airborne systems due to Ricean fading distribution. Equating the respective SNRs, we obtain the HAAP transmitter power P_H expressed in terms of the terrestrial-based transmitter power P_T,

$$P_H = \frac{G_T}{G_H} \frac{R_H^2}{R_T^n} P_T$$

From the typical parameter values it can be seen that the required transmit power per voice channel is 50 mW. Consequently, we need 1.5 W/CDMA carrier (assuming 30 voice channels/CDMA carrier). The total airborne transmitter power is therefore

$$50 \text{ beams} \times 8 \frac{\text{carriers}}{\text{beam}} \times 1.5 \frac{\text{Watt}}{\text{carrier}} = 600 \text{ W}$$

Even at 10 percent efficiency the transmitter's power consumption is 6 kW, which is well within the capabilities of any airborne platform. The capacity of this example system is calculated as:

$$50 \text{ beams} \times 8 \frac{\text{carriers}}{\text{beam}} \times 30 \frac{\text{CDMA channels}}{\text{carrier}} = 12{,}000 \text{ voice channels}$$

meaning that the system can serve 240,000 subscribers (assuming 0.05 Erlangs load/subscriber).

It has already been pointed out that HAAP-based telephone systems would avoid the cost of communications links required to connect geographically dispersed base stations that are required in terrestrial systems. This centralized architecture can also result in improved efficiency of channel utilization — a large trunk group is more efficient than multiple small ones. This is best described in terms of an example. Consider a suburban-type coverage area 150 mi in diameter, serving 100,000 customers. At busy-hour traffic loading of 0.05 Erlangs/customer, the total offered load is $A = 5000$ Erlangs. A terrestrial cellular system serving the area would have approximately 200 cells, assuming an average cell size of 10 mi in diameter. For simplicity, we take that the offered traffic is equally distributed among cells, and the traffic load per cell is $a = 25$ Erlangs. The number of wireless channels, n, needed to serve this population is obtained from the Erlang-B formula, $B(n, a)$ [3]. For $B = 0.02$, the blocking probability, tables show that $n = 34$ channels/cell are required, or 6800 channels for the entire coverage area. If a HAAP-based system is used to provide cellular coverage, the total offered load is served by a central facility. In such a case, the number of channels does not have to be dimensioned according to the busy-hour traffic but rather according to the average traffic in the area, since all available channels can be shared among all the cells and local traffic peaks are smoothed out (provided, of course, that the system has dynamic channel allocation capability). Using a conservative estimate, the average traffic is taken to be 70 percent of its peak value. To preserve the same grade of service, it is required that $B(N, 0.7\ A) = 0.02$, and the total number of channels for the area is $N = 3467$. This saving in the number of channels required means a reduction in the number of base stations when using HAAP-based systems, or an increase in capacity for the same number of base stations.

A potential for CDMA system capacity increase is seen in improving the accuracy of the power control algorithm. Namely, the more errors the algorithm makes, the more channel interference occurs, and the less the achievable capacity (the number of active voice channels). One decibel of error in power control, for example, is equivalent to 10 percent degradation in capacity [4]. Two main factors influence the errors in power control: the dynamic range of signal attenuation and the distribution of fast fades. Both factors are reduced in a HAAP-based system compared to the conventional terrestrial system. The dynamic range of signal attenuation in an ordinary terrestrial cell is 60–80 dB; of that, 40–50 dB is propagation-induced difference, and 20–30 dB is due to fading. In a HAAP system-formed cell, the dynamic range will be 12–22 dB, where 2 dB is propagation-induced difference and 10–20 dB are due to fading. In terrestrial cells, fast fades are typically Rayleigh distributed. In contrast to that, channels in a HAAP-based system are characterized by Ricean distribution of fades (like satellite channels,) yielding an additional energy gain which is a function of the Ricean factor, K. Typically, the range of K is 0–20 dB, and the larger its value, the higher the energy gain in HAAP-based systems compared to terrestrial ones, where K is close to zero (due to Rayleigh fading).

HAAP Issues

The focus of this article is on the communications systems that might one day be placed on HAAP technology. The most critical issues, however, are related to the platform itself — *it still remains to be demonstrated that placing a platform at stratospheric altitude and "fixing" it reliably above the coverage area is possible, and that it can be done in a cost-efficient, safe, and*

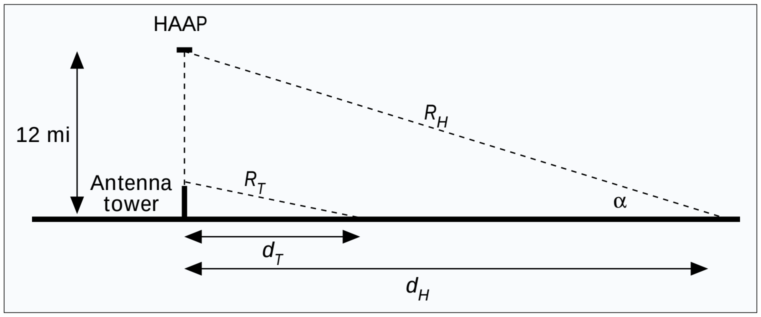

Figure 5. *Coverage of terrestrial and HAAP-based systems.*

sustained manner. These issues apply equally to high-flying planes and lighter-than-air craft.

Commercial aviation has amply demonstrated sustained, safe, efficient operation of all manner of aircraft, but at what altitudes? The legendary U-2 spy plane and its derivatives have shown that planes can fly at stratospheric altitudes, but for how many hours at a time, and at what cost? Dirigibles float safely over football fields; but would their basic design be extensible to stratospheric operation? Weather balloons are routinely launched to near-stratospheric heights for months or even years at at time, but what if their position had to be controlled precisely? Although considerable measurements of stratospheric winds have been made, how confident are we about gusts lasting a few hours or a few minutes? What about taking off and landing in varied weather conditions? What legal and regulatory hurdles might be erected by public policy bodies such as the Federal Aviation Agency, concerned with safety, or the Federal Communications Commission, concerned with spectrum usage? What proof willl be required, and how long will it take, for even a successful HAAP to gain wide market acceptance?

Clearly, a successful HAAP is not just the integration of available technologies, as some platform designers would have us believe, but rather a considerable extrapolation. Nonetheless, the extrapolation is not so great as to remove our optimism that solutions will be found, and HAAPs will one day become reaality.

There are also some communications issues that will need to be addressed — and there will undoubtedly be others that are not now apparent. For example, design and implementation of the required multibeam, steerable airborne antenna will not be an easy task. But there is a wealth of experience to draw upon from building such antennas for LEO satellites and high-flying planes. The antenna will have to be capable of producing up to several hundred "sticky" beams, that is, beams that will maintain their position on the ground as the HAAP flies in tight circles or bobs in the wind. A challenge this is, but one that should be doable through some combination of mechanical and electronic control (a phased-array antenna mounted on a motorized chassis).

Applications

The large coverage area of a HAAP wpuld tend to give it a competitive advantage over terrestrial alternatives in two types of applications. One is where *many widely separated customers receive the same communication*, as in entertainment broadcasting. The success of direct broadcast satellite (DBS) systems even in the presence of widely deployed cable TV in the United States is indicative of this opportunity. HAAP technology might be able to achieve many of the benefits of GEO-based DBS without having to transmit quite so homogeneously over so large an area. Unlike GEO-based technology, upstream channels should also be possible with HAAP, which would enable interactive TV and Internet access capabilities.

The other type of application in which a HAAP's large coverage area ought to be advantageous is in telecommunications for areas having a low density of customers, especially when prospective customers' specific geographic locations are unknown. The cost per customer of installing fixed facilities, such as wire, increases with decreasing customer density. This is especially the case when facilities need to be installed in locations where customers may or may not actually materialize. In cellular, PCS, and wireless systems, cost per subscriber tends to be less sensitive ato traffic densities than it is for wireline. But cost per subscriber of terrestrial wireless systems also rises when traffic densities get so low that many underutilized base stations have to be installed to achieve geographic coverage. In such low-density situations, both satellite and HAAP-based solutions become relatively more competitive vs. their terrestrial counterparts. In these circumstances, satellites have the advantage of even greater geographic coverage than HAAPs. However, HAAPs provide a quite large coverage area without giving up indoor signal penetration as with satellites. Also, HAAPs, unlike satellites, should be able to use much of the same equipment as terrestrial systems (especially the wireless phones themselves).

In certain applications, a single HAAP's coverage area of about 100 km radius would coincide nicely with a metropolitan area. For cellular or PCS services, for example, coverage of a metropolitan area is typically required in order to make it practical to advertise and support commercial service. Terrestrial wireless systems for similar initial coverage, although much quicker to deploy than traditional wireline networks, would require considerably more time and investment than the HAAP-based alternative. In this kind of rapid-deployment scenario, the HAAP-based system could even be temporary, to be replaced by more cost-effective terrestrial wireless or wireline technology as traffic volumes grow. Factors other than cost of build-out would also have to be weighed. HAAPs would eliminate highly visible antenna towers that sometimes cause public resistance to terrestrial systems, but would introduce concerns about objects falling from the skies. Because of the improved vantage point, HAAP-based systems should have better signal quality generally, and fewer "holes" in radio coverage, particularly when compared to terrestrial systems that have not yet been "fine-tuned." However, coverage in tunnels and deep basements would still require added repeaters or microcells.

A HAAP system whose coverage area is not too ambitious (e.g., look angle of 15° at the edge of coverage) will afford something closer to line-of-sight communications than a typical terrestrial wireless system. In terms of applications, this may be the best way to utilize some of the higher frequencies now being considered, such as LMDS, 38 GHz, 47 GHz, and so on. Such applications as very wideband Internet access, entertainment video and audio, and videoconferencing might be enabled by this technology.

HAAP technology, because it can be made to cover large areas quickly without having to rely on facilities in the service area, could be well suited to applications that are temporary or limited in scope. Examples of such services would be coverage for one-time or seasonal events, services for remote areas, temporary services in natural disasters or emergencies, and the maritime example discussed below.

Whatever the application, HAAPs could have some operational advantages over their terrestrial or satellite counterparts. Since typical HAAPs, unlike satellites, would be periodically brought to ground, repairs and upgrades of hardware would be possible. Depending on the specific design, of course, this accessibility may be less convenient than for terrestrial systems. Assuming that most of the communications equipment is centrally located in a ground station, system administration might actually be easier than for typical dispersed terrestrial systems. The single origin of the HAAP's beams that form coverage cells on the ground opens up the potential for flexible cell configuration with onboard programmability — a process that should be much easier than splitting a terrestrial cell and redesigning radio patterns to accommodate growth in terrestrial cellular systems. The fixed location of the HAAP could also be advantageous for situations in which end-user radios on the ground use directional antennas that are pointed to the signal source, as in a wireless local access system, for example. In that situation, the end-user radios could be reassigned to different cells (beams) without having to redirect their antennas. Of course, any operational advantages in terms of the communications would have to be weighed against the cost and operational complexity of the HAAP itself.

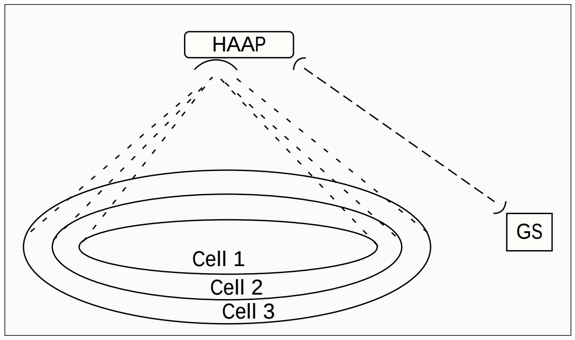

Figure 6. *Ring-shaped cells for airborne systems.*

Novel Solutions

This section exploress some novel solutions and applications for HAAP-based systems.

Ring-Shaped Cell Clustering Simplifies the Design of Steerable Multibeam Antennas

Traditional arrangement of cells in a hexagonal pattern covering the plane is a natural consequence of the way wireless coverage is provided in terrestrial systems. However, when coverage is established from an antenna mounted on a circling plane, or on an airship rotating around its central axis due to stratospheric winds, the "natural" cell shape is a geometric pattern invariant to such platform movements. Such coverage, made up of a set of concentric rings, is shown in Fig. 6. This arrangement is possible since cell shapes and their relative positions are of no consequence to the operation of a cellular system and, in fact, even has certain advantages over the traditional pattern. In that case each cell has just one or two neighbors, which simplifies handoff algorithms.

Cell Scanning Eliminates Complex Airborne Antennas and Saves Power by Focusing on Smaller Areas

The HAAP is particularly suited to taking advantage of emerging "smart antenna" technology. In fact, compared to its terrestrial counterparts in which sectorized antennas (beams) send and receive radio waves traveling along the ground, the HAAP's favorable "look angle" means that its energy can be more readily focused onto a confined area. A schematic view of this approach is shown in Fig. 7; it is similar to concepts used in some LEO satellite proposals (e.g., Teledesic). Depending on the application, it can be arranged that the beam "visits" a particular cell at regular or irregular intervals. Regular visits are suitable for real-time applications and services to meet quality-of-service criteria like delay and delay variance. Random times between visits can be used in non-time-critical applications such as Internet access.

While the beam is pointing to one of the cells, information is exchanged between user terminals and the communications equipment on the platform: the traffic intended for that cell is buffered in the interval between successive beam visits, and then beamed down in a burst manner; likewise, the information in user terminals is buffered until the control signal from the platform indicates that the beam is pointing to the cell, triggering the beaming up of information bursts. If one beam is not enough to satisfy the capacity or delay requirements, two or more beams can be used to scan the cells in a staggered manner. A variant of this approach is a system in which beams have different roles: "scout" beams scan the cells in search of those in which there are data ready to send in user terminals; "traffic" beams visit only the cells "marked" by scout beams, either randomly or according to some priority mechanism. All the described modes of operation will require an increase in buffering capabilities of end-user equipment and modifications in current air interface protocols.

Stratospheric Radio-Relay Maritime Communications System

Providing high-quality telecommunications service, including voice and data transmissions, for maritime vessels crossing world oceans is one of the most complex problems in telecommunications engineering. At present, only GEO satellite systems provide multichannel, long distance, reliable maritime commercial communication service. However, the existing maritime satellite user terminals are comparatively bulky, and satellite-based service is expensive. Use of the HAAP concept could solve the problem for a large part of the world ocean fleet. Namely, there are several major world ocean shipping lanes: across the North Atlantic; connecting West and South Africa; between Africa and Asia; between Africa and Australia; and between Asia and North America. Chains of HAAPs positioned above these lanes would operate as stratospheric radio-relay links, terminated by coastal radio centers at each end of the transoceanic link (Fig. 8). Operating frequencies for user, feeder, and inter-HAAP links are in the bands commonly used in satellite systems, current or proposed, but are only an example and are not essential to the operation of the maritime system. The system could provide multichannel, reliable, cost-efficient maritime communication service, including voice, data (e.g., Internet access), video, paging, and broadcasting.

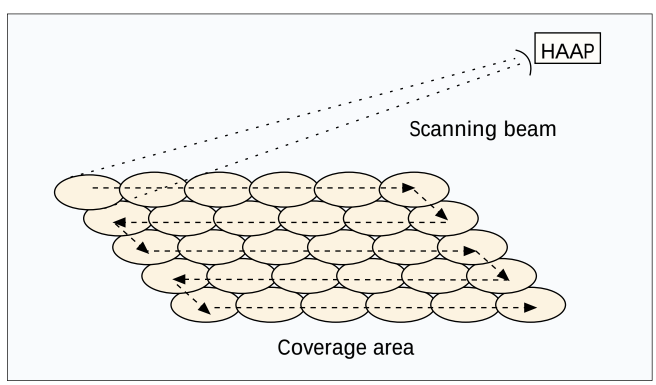

Figure 7. *Cell scanning from the airborne platform.*

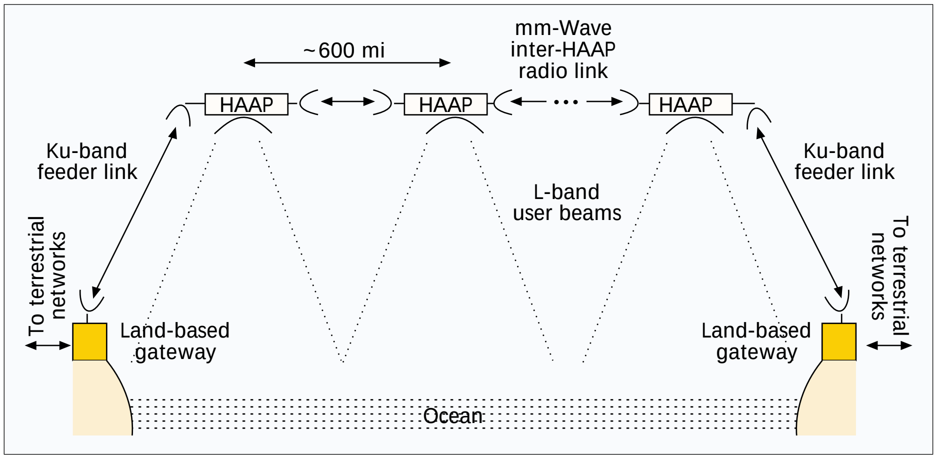

Figure 8. *Radio-relay maritime communication system.*

Platforms in Fig. 8 are shown as stationary, but the same concept would be possible to implement even if a platform moved at a relatively low speed along a racetrack-like path, for example, with endpoints close to land-based gateways.

Summary and Conclusions

This discussion has argued that high altitude aeronautical platforms (HAAPs) would be of considerable interest for wireless communications. Their position in the sky would give them many of the favorable characteristics of satellites, but without the distance penalty. Their position in the sky would also let them avoid the radio ground scatter of terrestrially based systems, while still being about as close, especially in terms of path loss, as terrestrial antennas. Thus, indoor coverage should not be a problem, as it is with even LEO satellites, and technology designed for terrestrially based wireless systems should be applicable. Since they collect traffic into a single point on the ground, HAAPs would reduce the amount and geographic extent of ground-based equipment vs. their terrestrial counterparts. HAAP-based systems would generally be more accessible for repairs and upgrades than satellites that have been launched, and, while the airborne portions may be less accessible than terrestrially based systems, the HAAPs' terrestrial components would be more accessible since they would be more centralized. The minimum system size for a single HAAP corresponds well to a metropolitan marketing region, facilitating rapid initial deployment for coverage so that commercial service can be started. The vantage point of HAAPs and the centralization of their beamforming apparatus would open new possibilities for smart antenna technology such as beam scanning.

Alas, if only there existed such technology as HAAP! As we have already observed, it remains to be demonstrated that placing a platform at stratospheric altitude and "fixing" it reliably above the coverage area is possible, and that it can be done in a cost-efficient, safe, and sustained manner. Nonetheless, considering the number and diversity of HAAP proposals, one is tempted to believe that some of them will be successful.

Acknowledgments

The authors wish to thank R. Myer, A. U. MacRae, F. Ludtke, and D. Hou for their valuable input and many discussions on the topic; and to the anonymous reviewers for their careful reading of the manuscript and thoughtful comments.

References

[1] J. Dicks, "Frequency Sharing Aspects of Networks Using Stratospheric Stations in the Fixed and Fixed Satellite Services," Doc. no. USWP-4A/32, Radiocommun. SG, ITU-R, June 27, 1996.
[2] W. C. Y. Lee, *Mobile Cellular Telecommunications*, 2nd ed., New York: McGraw-Hill, 1995.
[3] R. R. Martine, *Basic Traffic Analysis*, AT&T and Prentice Hall, 1994.
[4] A. J. Viterbi, *CDMA: Principles of Spread Spectrum Communication*, Reading, MA: Addison-Wesley, 1995.
[5] C.A. Robinson, Jr., "High-Capacity Aerial Vehicles Aid Wireless Communications," *Signal*, Apr. 1997, pp. 16–20.

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