A Broadband Wireless Access System Using Stratospheric Platforms

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Abstract - A Japanese national project for the development of stratospheric platforms (SPF) started in 1998 with the goal of constructing a new communications infrastructure. This paper describes this project, including the purpose, organizational structure, and current R&D activities. It focuses on the SPF-based broadband wireless access systems including the system scenario, system configuration, and services to be supported. Key technologies, such as the onboard multibeam antenna system and channel access schemes, are described.

I. INTRODUCTION

It has been a dream of communications engineers that a wireless system covering a wide service area anywhere should have the following characteristics: low propagation loss, little multipath fading, and the capability of providing various types of communications services. Terrestrial wireless communication systems that cover a broad service area, such as cellular systems, have low propagation loss but suffer from severe frequency-selective fading, which is mainly caused by the multipath effect. On the other hand, in satellite communication systems, both low earth orbit (LEO) and geostationary earth orbit (GEO), the communication link between an earth station and a satellite is line-of-sight but suffers from high propagation loss, which is caused by the long distance between satellite and ground stations. These deficiencies have prompted research into other types of communications platforms. Since the air current in the stratosphere at an altitude of 10 to 50 km is steady, it is possible to launch an unmanned airship and have it stay at a certain position in the stratosphere for a long time. Such an airship is called a stratospheric platform (SPF), and it can be used as a repeater and/or switching center for communications and broadcasting, a remote sensor and/or monitor for observation of the environment, and so on [1-6]. We believe that an SPF-based communication system offers a way of realizing this dream.

Airships and airships are candidate SPFs. Aircraft platforms have been proposed by Angel Technologies Inc. [3] and NASA [7]. Angel Technologies has advocated a low-cost manned jet plane for communication systems by using existing technologies. However, a jet plane discharges exhaust gases and thus may contaminate the high-altitude atmosphere. NASA has developed an unmanned light aircraft powered by solar cells that is mainly intended for earth observation. The feasibility of flying it in the stratosphere has been proved in demonstration flights. This kind of aircraft (with a maximum payload weight of 200 kg), however, is too small to carry communication and broadcasting mission payloads.

Proposals also exist for platforms using 150 to 260-m-long balloons filled with helium gas [1,5]. Such a balloon would have a self-supporting power supply system; power would come from the solar cells in the daytime and from fuel cells at night. The airship would have propellers driven by electric motors for keeping station and other necessary maneuvers. The airship approach is attractive because it is clean and can carry mission payloads of up to 1,000 kg. Sky Station International Inc. has proposed the use of 150-m-long airships at an altitude of 22 km for fixed wireless communication systems in the 47-48-GHz band and IMT-2000 mobile communication systems in the 2-GHz band [5].

A Japanese national project led by the Science and Technology Agency (STA) and the Ministry of Posts and Telecommunications (MPT) for the development of a balloon-based SPF capable of operating at an altitude of 20 km and carrying onboard mission payloads for communications, broadcasting, and environment observations started in 1998 [1,8]. It focuses on the R&D of key technologies for the airship and onboard missions and has the goal of applying these key technologies to a proof-of-concept demonstration SPF, which is scheduled to be launched into the stratosphere within five years. This paper's purpose is to give an overview of the project and to focus our R&D activities on broadband wireless access systems using SPFs.

The rest of the paper is organized as follows. Section II reviews the current activities on development of the airship. The configuration of the SPF-based broadband wireless access system is described in Section III. In Section IV, we discuss the key technologies required for the system.

II. AIRSHIP DEVELOPMENT

Although various SPF systems have great potential for constructing a new communications infrastructure, they are seen as being high-risk projects whose development will require a very large amount of human resources, a great deal of money, and large-scale facilities. The STA and MPT jointly began a national project to promote the development of the SPF in 1998. The project includes the development of airships, SPF-based communication and broadcasting systems, and SPF-based remote sensing systems. The main goal of the project is to develop the key technologies for the airship and mission systems within five years. At the end of the fiscal year of 2003, the project calls for a proof-of-concept demonstration of an experimental installation, including a 150-m-long airship launched into the stratosphere and various mission systems. For the communication and broadcasting mission, two broadband wireless access systems supporting fixed wireless access, a mobile communication system supporting IMT-2000, and a broadcasting system supporting digital television broadcasting will be developed and tested via various experiments. Figure 1 shows the timeline of the overall research and development effort.

A research group of the National Aerospace Labora-
tory of Japan started a feasibility study on an SPF using an airship filled with helium gas in the fiscal year of 1998 [9]. The airship had to be light and stable in high winds. In the stratosphere, as the altitude increases the wind speed decreases but the buoyancy of the airship decreases because of the rarefied air. The altitude from 20 to 22 km is considered to be appropriate for an airship to stay as a result of tradeoff. According to the data from the Meteorological Agency of Japan, the wind speed at this altitude may be over 30 m/s in winter but is calm during other seasons[8]. To keep station against 30m/s wind, a 200-m-long airship with propellers driven by electrical motors must be supplied with power from solar panels on its surface. Compared with same-sized pre-World-War-Two Zeppelins that flew at an altitude of 2 to 3 km, the weight of an airship of the same length that is designed for operation in the stratosphere should be reduced by a factor of 15. Table 1 lists the parameters of the airship that were the result of the feasibility study.

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<td>Svs. development</td>
<td>Experiment</td>
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**Fig. 1 Time-line of overall SPF R&D efforts.**

Table 1 Airship specifications and operating environment

<table>
<thead>
<tr>
<th>Items</th>
<th>Expected parameters</th>
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<tr>
<td>Altitude</td>
<td>20 to 22 km</td>
</tr>
<tr>
<td>Max anti-wind speed</td>
<td>30 m/s</td>
</tr>
<tr>
<td>Temperature</td>
<td>-56.5°C</td>
</tr>
<tr>
<td>Intensity of light</td>
<td>1.26 kwm²</td>
</tr>
<tr>
<td>Length</td>
<td>230 m</td>
</tr>
<tr>
<td>Weight</td>
<td>27,000 kg</td>
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The structure of the airship of the feasibility study is shown in Fig. 2. It has a semi-rigid structure hull with envelope of ellipsoidal shape, keel-structure in its lower part, and several internal helium gas-bags lifting up the keels through catenary curtains and ropes. With this structure, the airship will be safe even if gas escapes from one or more air bags. The onboard mission payloads and propellers must be installed on the keel-structure in the lower part of the hull. The orientation of the airship must be controlled so as to keep the airship upright and moving against the wind with a speed of 0 m/s relative to the ground. To do so, several onboard GPS (global positioning system) receive antennas should be installed. The life expectancy of the airship should be more than 10 years. During its life, the airship will return to the ground maintenance facility several times for inspection. The power of the airship, including the power supply for onboard mission payloads, comes from solar cells that generate several hundred kilowatts in the daytime. The energy is stored in fuel cells for use at night.

**Fig. 2 Design view of SPF feasibility study**

It will take several hours to launch an airship to an altitude of 20 km and to land it. Weather conditions are very important for launching and landing an airship since a strong wind can result in a crash. Thus, summer is the best season for the experiments. Wind profiles within a range of a dozen kilometers will be needed because the airship may be driven out when passing through the troposphere.

Though the specifications described above is for operational airship in the future, the proof-of-concept model will be smaller and the length will be around 150 m since the maximum anti-wind speed is designed to be 20 m/s. This value is enough for short-term experiments except for winter. The proof-of-concept model will be launched into the stratosphere and then flown back to the ground several times during a year to obtain the launching and landing experience as well as to change mission payloads for various experiments. Since lightweight fuel cells may not be available when launching the test flight model, the proof-of-concept experiments will be done in the daytime and/or using lithium-ion batteries.

**III. BROADBAND WIRELESS ACCESS SYSTEM**

The broadband wireless access system in the millimeter-wave band, providing megabits-per-second services for user terminals, is one of the third system scenarios of the communication/broadcasting onboard mission.

**III.1 System Scenario**

Figure 3 is an illustration of the communication and broadcasting systems of the SPF network. The system is composed of a number of aerial platforms and fixed or mobile terminals on the ground. A single SPF can cover an area with a radius of up to 100 km with an elevation angle greater than 10 degrees. This area is further divided into small service areas (cells) with radii of up to several kilometers, depending on the traffic density, by using a multibeam antenna system onboard the platform. As is the case in terrestrial cellular systems, the frequency reuse strategy, includ-
ing dynamic channel assignment, will be used to assign the cell frequencies. A number of onboard access points (AP), each corresponding to a cell, operate like base stations in terrestrial systems to support point-to-multipoint (P-MP) communications between the platform and user terminals. The AP and the terminals in a cell form an access subnet. On the platform, the APs are connected to an onboard switch that supports the inner- and inter-platform switching. The platforms are connected to each other via a point-to-point (P-P) gigabit optical link and form a trunk subnet. Thus, the trunk subnet provides a backbone for users while the access subnet provides wireless access to the backbone. Such an SPF communication network can be connected to public/private terrestrial wired or wireless networks via several high-speed P-P wireless links between platforms and gateway stations on the ground.

![Fig. 3. A stratospheric communication network.](image)

**III.2 Broadband wireless access (BWA) system**

Along with the basic system construction of trunk and access subnets, a BWA network will provide high-speed multimedia services to users with fixed terminals located in the service areas of SPF’s, which can be in metropolitan, suburb, or rural areas. Due to the relatively long propagation distance, frequency division duplex will be chosen. Since the communication path is line-of-sight, highly efficient modulation methods can be used, and thus, a maximum data rate of 100 Mbps in the downlink and a maximum 6 Mbps for a single user in the uplink can be expected. In addition, the size of the antenna in the terminal can be made as small as several centimeters in radius because the system will operate in the millimeter-wave band. Key technologies under development are described in detail in Section IV.

**III.3 Service Scenarios**

The BWA network will provide ATM- and IP-based services. Figure 4 shows the system configuration and network protocol model for IP service. The onboard equipment includes a multibeam antenna system, a number of APs with physical layer and DLC (data link control) layer components for wireless transmission and an Ethernet interface for connecting to onboard LAN, a number of HUBs, a router (or layer 3 switch), a P-P transceiver for interworking with terrestrial networks, an optical communication equipment for inter-platform transmission, and an authentication server.

![Diagram](image)

The protocol stack is shown in Fig. 4 (b). In this service scenario, the cost of developing the onboard mission equipment can be significantly reduced by using existing commercial LAN products. New equipment for wireless communications, including a multibeam antenna system, wireless modem, baseband signal processing components for MAC (medium access control)/DLC protocol, and wireless/mobility supporting router, must be developed.

![Diagram](image)

**III.4 Interworking with Terrestrial Networks**

To make use of plentiful information resources of terrestrial networks, especially, in the Internet, it is necessary for the stratospheric communication network, even though it can be independently self-configured, to connect to the terrestrial networks. The interworking function can be realized by the ground gateway station, as shown in Figs. 3 and 4. Except for the platforms that cover areas where it is difficult to build a ground station, such as sea, desert, etc., each platform should have at least one ground gateway station for interworking with terrestrial networks. The gateway station should maintain a high-capacity communication link with the platform and have a group of high-speed servers, switches and network gateways. The gateway responsible for exchanging packets stream between the SPF communication network and various kinds of terrestrial networks should
also be secure and have the ability of protocol translation.

Table 2 Main specifications of onboard antennas in different stages.

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<tbody>
<tr>
<td>Frequency</td>
<td>UHF: 2 GHz, 28/31 GHz</td>
<td>28/31 GHz, 47/48 GHz (UHF, 2GHz)</td>
<td>UHF: 2 GHz, 28/31 GHz, 47/48GHz, etc.</td>
</tr>
<tr>
<td># of beams</td>
<td>1-2</td>
<td>7-9</td>
<td>60-400</td>
</tr>
<tr>
<td>Max. elev. Angle</td>
<td>at some specific points</td>
<td>&lt;65°</td>
<td>20-45°</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>2-6 Mbps/carrier</td>
<td>&lt;25 Mbps/carrier</td>
<td>25-156 Mbps/carrier</td>
</tr>
<tr>
<td>Applications</td>
<td>DTV, WCDMA (test-pipe repeat)</td>
<td>BWA, etc. (onboard sw)</td>
<td>BWA, DTV, mobile com., etc. (onboard sw)</td>
</tr>
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IV. KEY TECHNOLOGIES FOR BWA NETWORK

Since stratospheric communication is a new form of wireless communications, key technologies for developing the system need to be studied. As indicated in Section III.3, these key technologies are concentrated in physical and MAC/DLC layers. The onboard multibeam antenna system and channel access scheme are described in this section.

IV.1 Onboard Multibeam Antenna System

IV.1.1 Requirements for onboard antenna

The radio access link of an SPF network using a band above 20 GHz is regarded as a power-limited channel, with small power margin like that in the satellite case, and is different from the links in terrestrial mobile systems. Thus, the onboard antennas must meet the following requirement.

- Use of directional antennas to get high e.i.r.p. and G/T.
- Use of a multibeam antenna system to get a large traffic capacity with efficient use of frequency. The minimum service elevation angle may be 20°, and the number of multibeam is about 60-400 for a single platform.
- Because the platform may fluctuate or drift because of variations in wind speed and pressure, the antenna’s beams should be controlled so as to compensate for these changes and to maintain a constant footprint on the ground as far as possible.
- Have a broad bandwidth to support data rates higher than 20 Mbps.
- Must operate reliably in the stratospheric environment.

IV.1.2 Basic characteristics of multibeam antennas

Due to time and budget limitations, the performance of the antennas onboard the test flight model will be very limited. Table 2 shows the main specifications preliminary of the antennas for each of the development stages. In the stratosphere, the temperature may be -60°C or lower, and the atmospheric pressure is about 50 hp. However, if the onboard equipment were designed to meet such environmental conditions, its development cost would be significantly increased. To avoid this, the temperature and pressure should be more or less controlled in the payload shelter. The parts and components for terrestrial use can then be used for mission payload onboard the test-flight model.

Two types of multibeam antennas, multibeam horn (MBH) and digital beamforming (DBF), are being developed for the test flight model. Each of the antennas has advantages and disadvantages. The antennas need to be evaluated in terms of their technical performance, cost, and the trend of associated technologies.

1) Mechanically controlled MBH antenna in 47/48 GHz band

Multiple beams are generated by an array of horn antennas. The horn antennas are mounted on a jambal base that is mechanically controlled in three axes so as to provide relatively fixed multiple footprints (one for each horn antenna). Typical features of this antenna are as follows.

- A broad bandwidth is achievable by using existing technologies. The development cost is low.
- Development and evaluation of RF devices takes commercialization into account because the antenna uses a band that has already been allocated worldwide.

Because the separations between transmission and reception frequencies is small, the spacing between transmitting and receiving antennas should be sufficiently long (10 m). The frequency reuse strategy is used to allocate frequency to footprints (cells), and the reuse factor depends on the side-lobe level of a single horn antenna. The side-lobe level of the antenna under development is designed to be -20 dB or less than the main-lobe level. This antenna is designed to support carrier transmission rates up to 25 Mbps. When the user terminal moves or the platform drifts vertically, hand-over between the beams will be needed.

2) DBF antenna in 28/31 GHz band

This antenna generates adaptive beams by the combination of an active array antenna and spatial digital signal processing. It features an intelligent next-generation antenna called a smart antenna, or, software antenna. In the receiving antenna, automatic acquisition, tracking and interference isolation can be achieved by spatial signal processing. In the transmitting antenna, retrodirective spatial power combining can be achieved by beamforming using the parameters given in the receiving antenna. The DBF antenna has been studied since 1980s mainly for military radar applications. Recently, it has been used for base station antennas in cellular systems to improve traffic capacity and service quality. This has resulted in a remarkable improvement in performance and reduction in size and cost of digital radio communication devices [10]. DBF antennas with many elements using frequencies of 10 GHz or higher, however, are not available for commercial use.

The antenna in the experiment will use the 28/31-GHz band (exactly, 27.5-28.35 GHz for uplink and 31.0-31.3 GHz for downlink), which was recently allowed for SPF communications use in WRC’00. Development costs can be kept to a minimum because this band has already been widely used in satellite systems. On the other hand, although the performance of digital devices is being rapidly improved, it may not be sufficient for real-time processing of multiple signals coming from many antenna elements of the array antenna. Consequently, the target data transmission rate for the test flight will be about 4 Mbps though a higher rate is expected.
in the near future. Thus, the development target of the DBF antenna is the establishment of a high-performance beam-forming capability rather than a high-speed transmission capability. The development and evaluation is also important for evaluating the feasibility of the ITU-R frequency allocation. The DBF antenna has the following features:

- A flexible beam steering for each terminal will be possible by using adaptive multiple beams. Fixed cells are no longer needed and thus traffic capacity is increased.
- The handover in the coverage area of one platform will not be needed except when two or more user terminals get too close to each other. High link quality is expected and the maximum antenna gain can be provided to each of the user terminals on demand.
- Spatial signal processing can reduce interference from undesired signals as well as reduce interference to other systems. The direction of arrival (DOA) of a communication signal or illegal radio can be estimated.
- Deflection of the antenna elements will not affect seriously the total performance of the array antenna.
- High-speed array calibration will be possible by using signal processing in the transmitting and receiving array.

Because there is little experience with the DBF antenna, the development cost will be more expensive than that of the MBII antenna. The power consumption may also be high. The DBF antenna for the test flight is thus designed to have as many as 16 antenna elements (4 by 4 square array) and is used to obtain technical data for future large-scale ones. The antenna will allow transmission of 5-10 carriers in one beam and 4 beams simultaneously available in transmit or receive. The number of signals also depends on the number of onboard modems.

Two types of digital signal processing devices are used: an FPGA/CPLD (field programmable gate array with complex programmable logic device) and a high-speed MPU (micro processing unit). The FPGA is suitable for high-speed parallel processing, and the MPU can be easily programmed. Table 3 shows specifications of the two antennas.

### IV.2 Channel Access Scheme

Efficient use of the limited frequency resources necessitates an efficient channel access scheme. FDMA, TDMA, and CDMA are well-known schemes for wireless systems. Combining them with onboard multibeam antennas gives rise to a new channel access technology for SF communication networks, called space division multiple access (SDMA). Therefore, the same channel, the same time slot, and the same code can be shared by different user terminals located in different directions from the platform, thereby giving efficient frequency reuse for a large number of users.

#### IV.2.1 Space division multiple access (SDMA)

Figure 5 shows the SDMA schemes combined with FDMA for two types of multibeam antennas. The fixed multiple beams generated from the MBII antenna form fixed ground cells that partially overlap (as in a terrestrial cellular system). Frequency reuse strategies can be applied to the system. The maximum achievable reuse factor depends on the side-lobe characteristics of the horn antennas.

| Table 3. Specifications of multibeam antennas for 150m class test model. |
|-----------------|-----------------|
|                | MBII antenna    | DBF antenna    |
| Frequency band  | TX: 47.3-47.5 GHz | TX: 27.3-28.3 GHz |
|                 | (LHCP)          | (LHCP)         |
|                 | RX: 47.5-48.2 GHz | RX: 31.0-31.3 GHz |
|                 | (RHCP)          | (RHCP)         |
| Number of elements | 7               | 16             |
| Type of elements | Corrugated horn antenna | Microstrip antenna |
| Number of multiple beams | Fixed beams: 7 | Fixed beams: 9, Adaptive beams: 3 |
| Antenna gain    | 19 dBi          | 15 dBi         |
| Saturated output power (TX) | >25 dBm | >16 dBm |
| Noise figure (RX) | <5 dB | <5.4 dB |
| Bandwidth       | >100 MHz        | >3 MHz         |
| Sampling rate   |                | 32 Mbps        |
| A/D quantization|                | 12 bits        |

![Fig. 5. SDMA with fixed and adaptive multibeam antennas. (f₁, ..., f₆: frequency bands, cᵢ, cⱼ: assigned channels, cᵢ ≠ cⱼ).](image)

The DBF antenna provides both fixed and adaptive multiple beams. The fixed beams may be used for an access control channel while the adaptive beams are used for traffic channels, offering spot beams directed toward each of the terminals on demand (beam-on-demand). The maximum traffic capacity of a channel also depends on the side lobe characteristics of the main beam. The side-lobe level can be easily controlled by amplitude weighting in the array antenna at the cost of beamwidth increase, whereas it cannot be controlled in the MBII antenna. Users can use same channel with the DBF antenna, as long as they separated from each other by some distance and the CIR (carrier-to-interference power ratio) degradation due to multiple co-channel signals does not exceed a permissible limit. The same channel cannot always be used with the MBII antenna even when the user locations separated by long distances because available channels are fixed to the ground cells. It is known from simulation studies that the adaptive multiple beams have at least double the capacity of fixed multiple beams does [11].

To achieve SDMA by the DBF antenna, we must overcome some algorithmic hurdles. Because the number of antenna elements in the array and required transmission rate are expected to increase in future commercial models, the number of computation should be minimized, fast acquisi-
tion and the antenna should be able to operate under low-
CNR conditions. Burst-type transmission in the packet net-
works will require. Fast acquisition will also reduce overhead
sequences for beamforming. An algorithm that meets the
above requirements is under investigation [12].

![Diagram of TDMA/SDMA Frame Structure](image)

**Fig. 6. Frame structure of a TDMA/SDMA scheme.**

### IV.2.2 TDMA/SDMA scheme

There are a number of MAC protocols for wireless
communication systems [13]. RS-ISA (reservation-based
slotted idle signal multiple access) protocol has been imple-
mented in millimeter-wave indoor high-speed wireless LAN
prototypes [14-16]. Combining the demand-assigned algo-
rithm of RS-ISA and the conventional channel access
scheme used in satellite communication systems, with the
features of MBH multibeam antenna system, we propose a
TDMA/SDMA protocol for an SPF BWA system. The frame
structure of the protocol is shown in Fig. 6.

The TDMA/SDMA protocol is a MAC protocol that
lets a user terminal access the shared broadband channel
provided by the beam generated by the MBH antenna sys-
tem. Actually, it is a dynamic TDMA/FDD scheme with a
frame-slot configuration. As shown in Fig. 6, both uplink
and downlink frames have the same durations. The uplink
and downlink channels, however, may have different data
bandwidths to support asymmetric transmission data rates.
A frame consists of a number of time slots. There are two
types of time slots. One is for transmitting control infor-
ma and the other is for transmitting data. The length of
a data time slot is \( n \) times the control time slot, where \( n \) is an
integer. The time offset between the uplink frame and
downlink frame is \( 1/2 \) the frame length in order to compen-
sate for the propagation delay.

At the beginning of a downlink frame, the AP broad-
casts a timing offset adjustment and the uplink channel's
slot assignment information. The user terminals use this
information to adjust the transmission timing and decide to
transmit a reservation packet when it accesses to the chan-
nel with a newly generated traffic and/or transmit one or
more data packets at the assigned data slots. When more
than one terminal simultaneously transmit reservation pack-
et at the same reservation slot, a collision occurs. A collid-
ed terminal retransmits the packet after a random delay.
After a successful reservation, the AP assigns data slot(s)
according to the terminal's request. This protocol also sup-
ports link layer retransmissions. ACKs or NACKs (positive
or negative acknowledgment) for control packets and data
packets are transmitted in RACK and DACK time slots,
respectively. Demand-based assignment of data slots allows
this protocol to support multimedia traffic transmissions.

**V. CONCLUSION**

This paper described an SPF system for high-speed
wireless access network and a national project whose goal is
the demonstration of a proof-of-concept system by 2003.
The network configuration, system scenario, and service
scenarios of a BWA system using SPF were described. The
key technologies related to the design of the multibeam an-
tennas to be put onboard test flight model and the channel
access scheme were also described in detail. Many other is-
 issues remain for further investigation, such as detailed ac-
cess control schemes, handover between adjacent platforms,
modulation/coding schemes, network routing schemes, and
so on. The system design process requires cooperation
among industries, academia, and government and should
take into account trends in technologies and the market.

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