EXPERIMENTAL FIXED AND MOBILE MULTIBEAM SATELLITE COMMUNICATIONS SYSTEM

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ABSTRACT

Multibeam satellite communications systems are expected to play an important role in constructing economical and highly reliable communications networks in combination with terrestrial networks. They will provide attractive new communications services promptly and widely. NTT is making intensive efforts in the research and development of multibeam satellite communications systems and is planning to carry out flight verification of the system using Engineering Test Satellite-VI (ETS-VI) which will be launched in 1992. This paper describes the configuration and characteristics of the experimental systems for fixed and mobile satellite communications.

1. INTRODUCTION

Satellite communications systems have a number of advantages over terrestrial systems, including flexibility, rapidity and ease of network construction. Satellite systems are expected to play an important role in constructing economical and highly reliable networks in combination with terrestrial networks.

Nippon Telegraph and Telephone Corporation (NTT) has been carrying out research and development work for domestic satellite communications systems since the 1960's. The commercial domestic satellite system in Japan started with two communications satellites (CS-2a and -2b) launched in 1983. They were succeeded by the CS-3a and -3b launched in February and September, 1988. This system employs a conventional single beam communications technology using the Ka-band (30/20 GHz) and the C-band (6/4 GHz) and puts some restrictions on the size of earth station antenna and capacity.

To overcome the limitations of single beam systems, a lot of research and development has been made into high capacity multibeam satellite communications systems. Multibeam satellite communications systems are effective for increasing the signal power flux density at earth stations by narrowing the beam width with a large onboard antenna. The increased signal power flux density has significant advantages for increasing the transmission capacity and allowing the earth station to be smaller and more economical.

NTT has been developing various technologies to implement multibeam satellite communications systems for domestic use. To realize a multibeam satellite communications system, it is essential to confirm the performance of onboard equipment completely before actual utilization. Since it is very difficult to simulate the space environment completely using only terrestrial facilities, the final evaluation should be actually carried out in space.

NTT is participating in the ETS-VI program by developing onboard equipment for fixed and mobile satellite communications systems and is preparing for the evaluation and verification of newly developed fixed and mobile communications systems using a geostationary satellite. (1,2,3)

This paper describes the outline, configuration, and features of the experimental multibeam satellite communications system in the ETS-VI program.

2. SYSTEM OUTLINE

The purposes of the experiments are:
(1) Space confirmation of onboard equipment performance necessary for multibeam system implementation.
(2) Function and performance evaluation of the total system including satellite and earth stations

A multibeam satellite communications system requires large, accurate, deployable antennas, an accurate antenna pointing system, a satellite switch, small light transponders and supervisory & control circuits as onboard equipment. These technologies have never been verified in space.

The multibeam satellite communications system image for fixed and mobile communications experiments is shown in Fig. 1. This system employs three frequency bands, Ka-band (30/20 GHz), C-band (6/4 GHz), and S-band (2.6/2.5 GHz, with the antenna coverage shown

52.4.1.

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The main advantages of the multibeam system are earth station size reduction, transmission capacity increase and frequency reuse among beams. To take maximum advantage of the multibeam system, the experimental fixed communications systems are composed of high bit rate TDMA systems up to 200 Mbps, medium bit rate TDMA systems with small earth stations, multi-carrier systems with very small aperture terminals and other systems to confirm the advantages of the multibeam system and compatibility with the present single-beam system.

A satellite switch to transfer traffic between different beams is essential in a multibeam fixed system. IF (Intermediate Frequency) and RF (Radio Frequency) switches have been selected for development as the satellite switch. All the signals in every band (Ka-band, C-band and S-band) are connected by the IF switch so that maximum system flexibility can be achieved.

A number of new techniques have been applied to enhance the multibeam and satellite switch advantages. They are Satellite-Switch (SS)-TDMA incorporated with demand assigned satellite switch operation, cross-band interconnection associated with cross-band diversity, single-beam/multibeam system interconnection and band selective switching.

NTT verified the basic technologies of multibeam mobile communications through the field trials of the Experimental Mobile Satellite System (EMSS) using Engineering Test Satellite-V (ETS-V)\(^{4}\). A new multibeam system called Dynamic Channel assigned Multibeam Satellite (DCMS) system was proposed for the mobile communications system to enhance traffic flexibility\(^{5,6,7}\). The ETS-VI multibeam experiment is also planned to confirm the feasibility of the DCMS system using the S-band allocated for mobile satellite services in ITU Region 3 in WARC-79.

3. Onboard system configuration

The onboard communications system configuration was designed to meet the above-described requirements and is shown in Fig. 2. Since ETS-VI includes other mission equipment besides the fixed and mobile communications systems, the mass and power allocated to the system is limited. Transponders are as a result not installed to all antenna beams but a sufficient number of transponders are installed to confirm the multibeam transponder performance and also system performance. The estimated mass and DC power of the multibeam communications system can be kept within 300 kg and 1.25 kW respectively.

Multibeam antennas are composed of main reflectors with 3.5/2.5 meter diameters, sub-reflectors and highly accurate antenna pointing systems. When used for Ka-band fixed communications, it covers the Japanese main islands with thirteen 0.3-degree-wide spot beams. When used for S-band mobile communications it covers the area within 200 nautical miles from the Japanese coast with five beams. Most traffic in Japan is concentrated in two restricted areas, namely Tokyo and Osaka. The actual capacity is primarily determined by the frequency band allocated to these areas. Frequency reuse between Tokyo and Osaka is thus considered in addition to cross-polarization use in the same beam. As the angle between these two cities is about 0.7 degrees, the cone angle of the spot beam has to be less than this value.

An IF switch is composed of 16x12 IF gate switches controlled by a Satellite Switch Controller (SSC). In addition to the IF switch, an RF switch is installed after the TWTA to enhance the flexibility of traffic allocation.

For mobile communications, radio channels are flexibly assigned by employing an onboard transponder system called multiport amplifier (MPA). The MPA can assign the total power or total channel number to each beam in any ratio. In an extreme case, for example, all power or all channels can be concentrated into any one beam.
4. SYSTEM FEATURES

4.1 Function

(a) Demand assigned satellite switch operation

In a multibeam satellite communications system, an onboard satellite switch is required to interconnect uplink beams and downlink beams. The satellite switches proposed thus far are classified into two types: an IF/RF switch which connects uplink beams with downlink beams at an intermediate frequency stage or radio frequency stage, and a baseband switch which handles demodulated baseband signals.

The former switch operates conventionally with fixed switching patterns, while the latter switch operates with dynamic (call-by-call) switching patterns. A baseband switch has the advantages of interchanging the time slot position in the TDMA frame and offering higher throughput performance than an IF switch. However, an IF switch requires less hardware and is more flexible for various signal transmission than a baseband switch. For ETS-VI, in order to achieve high throughput performance with an IF switch, a dynamic switch control scheme was applied for the first time.

The satellite switch and satellite channels are centrally controlled by a control station. When a calling request is transmitted to the control station, it searches for an idle time slot and transmits burst assignment data to the earth stations via a satellite link at the same time as transmitting the switch control data to the onboard SSC. An example of the control system configuration is shown in Fig. 3. The SSC controls the IF/RF switches in accordance with the control data stored in the SSC memories similar to the fixed operation. The control station controls the satellite switch on a call-by-call basis through the SSC.

![Satellite switch control system configuration](image)

Fig. 3 Satellite switch control system configuration

![Experimental System Configuration for Multibeam Communications in ETS-VI Program](image)

Fig. 2 Experimental System Configuration for Multibeam Communications in ETS-VI Program

52.4.3.
(b) Cross-band interconnection

The IF switch interconnecting all-band receivers and transmitters implements new functions such as cross-band diversity and one-hop connection between earth stations with different frequency bands in addition to feeder-link connection for the mobile system. A multibeam system is associated with high frequency bands suitable for spot beams. In such high frequency bands, rain attenuation is a serious problem. Increases in G/T and e.i.r.p. by employing a multibeam satellite have the effect of decreasing rainfall outage probability, but transmission capacity increase and earth station size reduction are thereby sacrificed. Several adaptive schemes have been proposed to cope with rainfall outage such as coding control, satellite transmission power control(10) and site diversity. However, the improvements in unavailability provided by these technologies are limited to the order of $10^{-1}$ to $10^{-2}$ (%/year) for the Ka-band in practical systems. Other schemes are being sought to achieve lower unavailability. Cross-band diversity is applied to this system to improve the unavailability.(11)

When Ka-band channels are interrupted by rainfall, C-band channels are assigned to the uplinks and/or downlinks. Thus, the C-band channels are employed as cross-band diversity channels for Ka-band multibeam channels.

(c) Single-beam/multibeam system interconnection

One of the most important satellite communications advantages is that since widely distributed traffic is concentrated in a satellite transponder, the satellite channels can be shared by many earth stations and assigned to any earth station at any time. In a conventional multibeam system, since satellite channels must be divided in a fixed manner to transmit to the spot area covered by multiple beams, the sharing effect is limited to some extent. However, the ETS-VI system has superior traffic performance in addition to practical rainfall outage characteristics.

A single-beam system accommodates all the traffic until all transponder capacity is occupied. However, in a multibeam system, since transponder channels are assigned to each beam in a fixed manner, traffic loss is caused by traffic variation among beams even if total transponder capacity has room for all the traffic. The ETS-VI system overcomes this multibeam handicap by combining C-band single-beam and Ka-band multibeam systems.

The multibeam channels are assigned to each channel demand with first priority in uplinks and downlinks independently. When multibeam channels are interrupted by blocking, single-beam channels are assigned to the uplinks and/or downlinks. Thus, the single-beam channels are employed as common alternate channels for multibeam channels.

(d) Band Selective Switching

A multibeam communications satellite increases satellite e.i.r.p. and G/T. As a result, a transponder can transmit multiple medium bit rate carriers to small earth stations as well as a single high bit rate carrier to relatively small earth stations. When multiple carriers are transmitted, transponder nonlinearity causes intermodulation and degrades transmission performance. The Ka-band suffers from large rainfall attenuation, and it is necessary to make all signal levels uniform to avoid degradation of lower-level signals(12). To achieve this, ETS-VI transponder employs a Filtering Level-control Circuit (FLC) between receivers and IF switch, as shown in Fig. 4. In Fig. 4 the FLC equalizes the levels of two medium bit rate channels after forming three channels, a high bit rate channel, an upper medium bit rate channel, and a lower medium bit rate channel. Each channel is connected to a desired transmitter by the IF switch which has the functions of combining two upper and lower channels, distributing a signal from a certain receiver to multiple transmitters simultaneously, and connecting unnecessary signals to a dummy port. Thus, this system makes it possible to transmit not only a single high bit rate channel in certain time slots but also two medium bit rate channels coming from different beams in the other time slots. In this way, it makes efficient use of the transponders.

Fig. 4 Band selective switching circuit concept

(e) High power RF switching

One of the problems in implementing a multibeam system concerns efficient utilization of the transponders, when the traffic demands of each beam area are nonuniform. It is not
efficient to have transponders for all beams, especially low traffic beams. High power RF switching is applied to this system to improve transponder utilization.

This concept is shown in Fig. 5. The RF switching circuit, which is controlled by SSC, divides the TWTA output power into different low traffic beams in a time-division manner. In this way, this system makes it possible to efficiently use a transponder for several light traffic beams.

![Fig. 5 High Power RF Switching Concept](image)

(f) Dynamic channel assignment with multiport amplifier

A multibeam system improves the mobile terminal economy and increases transmission capacity. Flexible use of radio channels is desirable for implementation of a better multibeam system, since conventional multibeam systems have the drawback that radio channels of satellite transponders must be allocated in a fixed manner to each beam. In response to this demand, ETS-VI adopts a new multibeam system called Dynamic Channel assigned Multibeam Satellite communications (DCMS) system. The DCMS system employs a transponder with an MPA. The system configuration is shown in Fig. 6. For forward links in Fig. 6, SCPC signals are transmitted from a satellite mobile base station (SMBS) to the satellite. The received signals are divided into five groups after passing through an LNA and a frequency converter (CONV). Each of them is band-limited at the band-pass-filter (BPF). Then, they are converted to the same 2.5-GHz band, and supplied to the MPA. The MPA outputs are transmitted to mobile terminals in each beam zone.

For the return link in Fig. 6, a mobile terminal transmits an SCPC signal on the 2.6-GHz band. A group of SCPC signals from each beam independently pass through LNA, CONV and BPF, and are combined. The combined signal is transmitted, through CONV and a high power amplifier (HPA), to a SMBS.

For these operations, channel assignment SCPC signals are dynamically controlled. The SCPC signals to beam number i (i = 1, 5) are assigned to the frequency range of beam number i in the feeder link frequency band, as shown in Fig. 6. In addition, to avoid interbeam interference, radio channels are allocated so as not to overlap the frequency positions in the mobile link frequency band. Furthermore, the local oscillators of the CONV's for each beam are used in common. Automatic frequency control can therefore be performed by a specific beam using only one pilot signal.

When the traffic concentration rate is defined as the ratio of the number of allowable subscribers in a specific beam to the total number of system subscribers, the number of allowable subscribers decreases as the traffic concentration rate increases in a conventional system. This means excess radio channels must be reserved for each beam in order to carry the

![Fig. 6 Dynamic Channel Assigned Multibeam System Configuration](image)
traffic volume of imbalanced subscriber distribution. On the other hand, the DCMS system can be equivalently viewed as a single-beam system. The allowable number of subscribers can be kept constant independent of the traffic concentration rate. Also, in a conventional system, when an HPA failure associated with a specific beam occurs, the system does not work for the specific beam. However, in the DCMS system, although an HPA failure in the MPA reduces the total output power, it does not cause fatal damage to the system. Thus, the DCMS system delivers high throughput and reliability performance.

4.2 Onboard antenna system

(a) Reflector and feeder system

The onboard antenna system configuration is shown in Fig. 7, and the antenna requirements are shown in Table 1. Major features of the antenna system are: reflector co-use for 30 GHz/C-band and 20 GHz/S-band, Ka-band frequency reuse among beams and cross-polarization use within the same beam, low sidelobe level, a module concept to enable parallel development with the satellite bus.

One of the important factors to be considered is the large diameter reflectors. The main and sub-reflectors have to be folded during the launch phase because of the comparatively small volume of the vehicle fairing. They are then deployed and erected to the desired position after the satellite is placed in the geostationary orbit. FSS's (Frequency Selective Surfaces) are used to enable reflector reuse for different bands.

As for the Ka-band system, the sidelobe level has to be made low so that frequency reuse between Tokyo and Osaka can be realized. This requirement is satisfied with very high reflector surface accuracy (0.2 mm RMS) and a very sophisticated feeder system. Using cluster feeder assemblies composed of small diameter horns, the sidelobe level between the Tokyo and Osaka beams can be suppressed to less than -35 dB.

The antenna structure, namely main reflectors, sub-reflectors and tower, are fabricated of CFRP (Carbon Fiber Reinforced Plastics). The main reflectors have a CFRP truss-type backstructure to satisfy requirements such as mass, stiffness and low thermal distortion. The antenna subsystem weighs about 150 kg (including all the components stated in this section).

(b) Antenna pointing control system

Another important technology related to this antenna is the antenna pointing control system. The narrower the beam, the more accuracy is required in pointing. The D/U ratio requirement between the Tokyo and Osaka beams is again the determining factor for the pointing accuracy. To keep the beam direction within one 20th of the beam diameter, an antenna pointing control system is necessary in addition to the satellite attitude control system. In order to achieve this level of pointing accuracy (0.015 degrees), an RF sensor which employs the same antenna system and frequency band as the communications system has been developed(14).

Tilting the reflector mechanically around the two orthogonal axis, the longitudinal and latitude component error can be compensated. Although rotating error can't be compensated with this method, this error can be kept sufficiently low by controlling the satellite yaw attitude error to within 0.15 degrees. By considering the control bandwidth and the required error budget, a sub-reflector was selected as the controlling reflector.

4.3 Transponder System

Main characteristics of the experimental transponder systems are summarized in Table 2.

(a) Satellite Switch

The complexity of the switch matrix is proportional to the product of input and output port numbers. To satisfy the communications system requirements, the IF switch has 16 by 12 input and output ports. A monolithic switch IC module has been developed to reduce the switch matrix size and mass. To meet the required transient performance in the SS-TDMA system, a monolithic GaAs switch IC and a driver IC with switching speeds of 10 nanoseconds or faster has been developed.(15)

A high power RF switch, which switches the TWTA RF output power between two spot beams within 50 nanoseconds, is also developed to increase the flexibility of transponder use.

One feature of the satellite switch is its capability to switch on a call-by-call basis. This function is effective in increasing transmission efficiency. An SSC satisfying this requirement has been developed which is capable of changing switching patterns every 8 microseconds. The SSC uses a CMOS microprocessor, an 8k-gate CMOS Gate Array and a 64 kb SRAM to satisfy mass and power requirements. To implement the SSC, circuit technologies for the LSIs and high capacity memories have been developed for the space environment, in particular to achieve the required radiation hardness. As the IF switch matrix and SSC are key components in a multibeam transponder, the IF switch has 100% redundancy at each cross point and the SSC adopts 2 out of 3 redundant systems.

52.4.6.
(b) Small size and light weight transponder

Small size and light weight transponders for the Ka-band and the C-band have already been developed for the CS-3 satellite.(16) In a multibeam system, the size, mass and power efficiency of the transponder become more and more important as the number of transponders increases. For this reason, further development has been conducted to reduce transponder weight, size and DC power consumption as well as to improve performance characteristics.

As for the Ka-band transponder, a 30-GHz-band MIC low noise amplifier (LNA) using a HEMT (High Electron Mobility Transistor) device,(2) small-size, lightweight up/down frequency converters using MIC and MMIC technology,(17), a 10-W small-size TWTA and 20-GHz-band all solid-state transmitter have been developed.

For the C-band, an all solid-state transponder with a 7W GaAsFET SSPA is employed. To reduce the transponder weight, magnesium was used for the housing material of almost all Ka-band, C-band and S-band components. Also, several miniaturized Hybrid IC modules have been developed for the circuits which are used in many components (such as the IF amplifier, the power supply and the local oscillator) to reduce weight and cost.

In a SS-TDMA system, the frequency deviation between bursts should be kept as small as possible, so that the receiver local signal references are supplied from a common oscillator.

(c) New Technology realizing the DCMS System

One of the features of mobile satellite communications is that rather large traffic distribution fluctuations exist among various beams. A very unique amplifier system, called the MPA (Multi-Port Amplifier), was developed to cope with this traffic variation. Several new technologies are also necessary to realize the DCMS system, and hence the following new technologies have been developed.

(1) 100 Watt MPA
(2) Frequency conversion and stabilization
(3) Multiplexer/Demultiplexer with steep skirts
(4) High power, high isolation, low loss diplexer

Figure 8 shows a block diagram of the MPA. The MPA is composed of 8 GaAs high power amplifiers, power divider and combiner circuits(18,19). It makes effective use of DC power independent of the traffic variation. The MPA produces 100 W output power in the 2.5-GHz band.

Table 2 Main Characteristics of Experimental Transponder System

<table>
<thead>
<tr>
<th>Item</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Weight/Small Size Transponder</td>
<td>- Bear-chip IC Module for RF and IF circuits - Magnesium Housing - High Switching Frequency Power Supply (400kHz)</td>
</tr>
<tr>
<td>30 GHz-band HEMT LNA</td>
<td>- NF S 4.4 dB at 30 GHz - Gain 28 dB</td>
</tr>
<tr>
<td>30GHz-band MMIC</td>
<td>- 30 GHz-band Full MMIC Receiver</td>
</tr>
<tr>
<td>Multi-Port Amplifier</td>
<td>- Pout = 100 W at 2.5 GHz - 8 Linearized GaAsFET HPAs - Compact Low loss Power Divider/Combiner</td>
</tr>
<tr>
<td>Solid State Power Amp</td>
<td>- Pout = 7 W at 4 GHz - Pout = 1 W at 20 GHz</td>
</tr>
<tr>
<td>Light Weight TWTA</td>
<td>- Pout = 10 W at 20 GHz - Weight &lt; 1.65 kg</td>
</tr>
<tr>
<td>Satellite Matrix Switch</td>
<td>- GaAs MMIC Switch Module, Matrix Scale 16 x 12 - Switching Speed &lt; 10 nsec</td>
</tr>
<tr>
<td>High Power RF Switch</td>
<td>- Handling Power ≥ 10 W at 20 GHz - Switching Speed ≤ 50 nsec</td>
</tr>
<tr>
<td>Switch Controller</td>
<td>- CMOS Microprocessor - CMOS Gate Array (8k gate) - SRAM (64kb)</td>
</tr>
<tr>
<td>Narrow Band Filter</td>
<td>- 1GHz-band SAW Filter - High isolation Diplexer at 2.6/2.5 GHz</td>
</tr>
<tr>
<td>High Stable Oscillator</td>
<td>± 5 x 10⁻⁹ / -10° + 40°C</td>
</tr>
</tbody>
</table>

Fig. 7 Antenna System Configuration

Table 1 Antenna requirements

<table>
<thead>
<tr>
<th>Frequency band (GHz)</th>
<th>Ka-band</th>
<th>30/20</th>
<th>C-band</th>
<th>S-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam number</td>
<td>13</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>48</td>
<td>35/33</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>2.5m/3.5m</td>
<td>2.5m</td>
<td>3.5m</td>
<td></td>
</tr>
<tr>
<td>Frequency re-use</td>
<td>Tokyo/Osaka</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>V and H (within a beam)</td>
<td>V and H (within a beam)</td>
<td>R or L (within a beam)</td>
<td></td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>0.015</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>
4.4 Supervisory and Control System

In a multibeam communications satellite, the number and functions of the transponder generally increase. Furthermore, since it is essential for the IF switch to be controlled on a demand-assignment basis, a relatively high bit rate (65 kb/s) control link from the ground control station is necessary. An onboard Communications equipment Supervisory and Control equipment (CSC) has been designed to satisfy these requirements. Control and telemetry information is transmitted through the Ka-band data link and MODEM, separately from the satellite TT&C. The CU (Central Unit) handles all the information and, using the onboard data bus, distributes the signal to the RU (Remote Unit) and the BIU (Bus Interface Unit, a special RU to interface SSC). To realize this type of distributed control system, mass and power consumption of the equipment must be minimized. Four kinds of LSIs have been developed including an analog/digital circuits-implemented LSI which handles usual analog control and telemetry signals.

5. CONCLUSIONS

This paper has described the experimental systems for fixed and mobile satellite communications in the ETS-VI program. NTT has completed the development of the key technologies, and a flight model of the equipment is now undergoing performance testing.

ACKNOWLEDGEMENTS

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