Multibeam Phased Array Feed System Using Beam Group Concept

Yoshinori Suzuki†, Akira Meguro, Kiyoshi Kobayashi, and Masazumi Ueba

Abstract

The concept of beam groups should enable us to obtain a lightweight antenna feed system that offers high antenna gain and high flexibility in radio-frequency (RF) power distribution among the beams of the next-generation multibeam communication satellite. Setting up groups of beams and exciting all the beams in a group using the same amplitude weight improves the antenna gain over the entire coverage area compared with the conventional array-fed reflector antenna and achieves flexible RF power distribution among the beams. The beams shared by different beam groups are combined with appropriate phase and division ratios so as to further improve the RF power distribution flexibility. An antenna feeder that uses these techniques is only half the weight of conventional antenna feed systems.

1. Introduction

The design of an S-band next-generation broadband scalable mobile satellite communication system for the ubiquitous network [1] will require various innovations to reduce the weight and power consumption of the onboard equipment. The required capacity of 1 Gbit/s can be achieved by using a multibeam system that offers high-antenna-gain beams and extremely high levels of frequency reuse. Moreover, the radio frequency (RF) power resource allocated to each beam must be varied to match the beam's traffic [2]. The typical approach to achieving these goals is to use a reflector antenna with a multibeam feeder. Two major technologies are important for the onboard antenna system: an ultralightweight large antenna reflector [3] with an aperture diameter of about 20 m and a lightweight 100-beam-class antenna feed system.

This article describes a novel multibeam antenna feed system that uses the concept of beam groups. In each group, all the beams are excited using the same amplitude weight. This improves the antenna gain over the entire coverage area compared with the conventional array-fed reflector antenna and achieves flexible RF power distribution among the beams. To further improve the RF power distribution flexibility between beams, we devised a beam-forming method that combines beams from different beam groups. We used these methods to design an onboard multibeam reflector antenna for a broadband scalable mobile satellite communication system. We confirmed their validity by calculating the expected antenna performance. These new methods enable the weight of the onboard multibeam antenna feed system to be reduced by about 50% compared with the conventional methods.

† NTT Access Network Service Systems Laboratories
Yokosuka-shi, 239-0847 Japan
Email: suzuki.yoshinori@lab.ntt.co.jp

2. Requirements for onboard antenna systems

Our aim is to make the next-generation broadband scalable mobile satellite communication system by building an S-band 1-ton-class geostationary satellite with a communication capacity of up to 1 Gbit/s [1]. The weight budgets for onboard equipment are shown in **Fig. 1**. To meet these budgets, we must halve the weight of the antenna feed system.

Achieving a 1-Gbit/s capacity in the 30-MHz bandwidth allocated to mobile satellite services in the S-band requires frequency reuse in excess of 20 times.

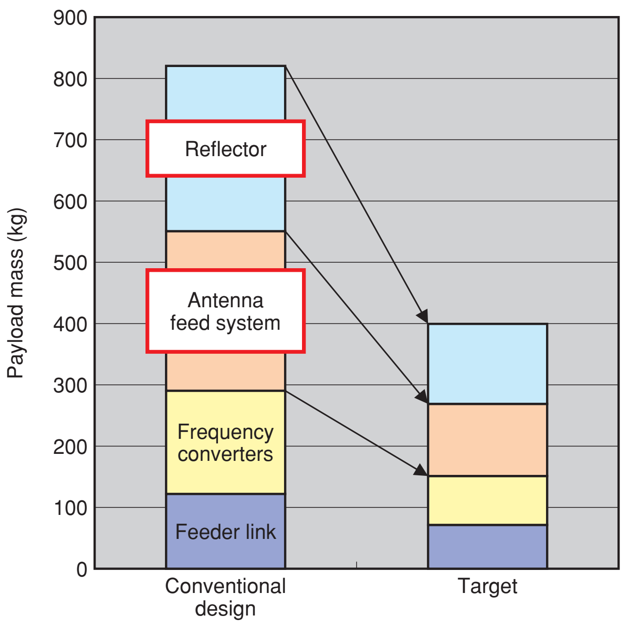


Fig. 1. Weight budgets for onboard equipment.

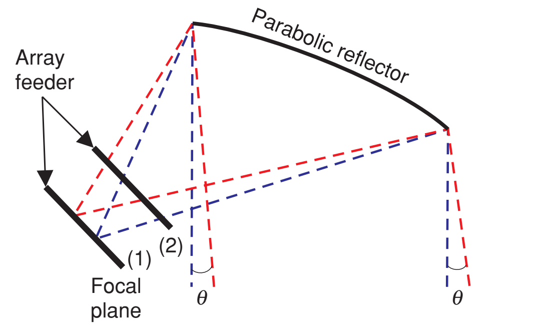


Fig. 2. Configurations of multibeam reflector antennas.

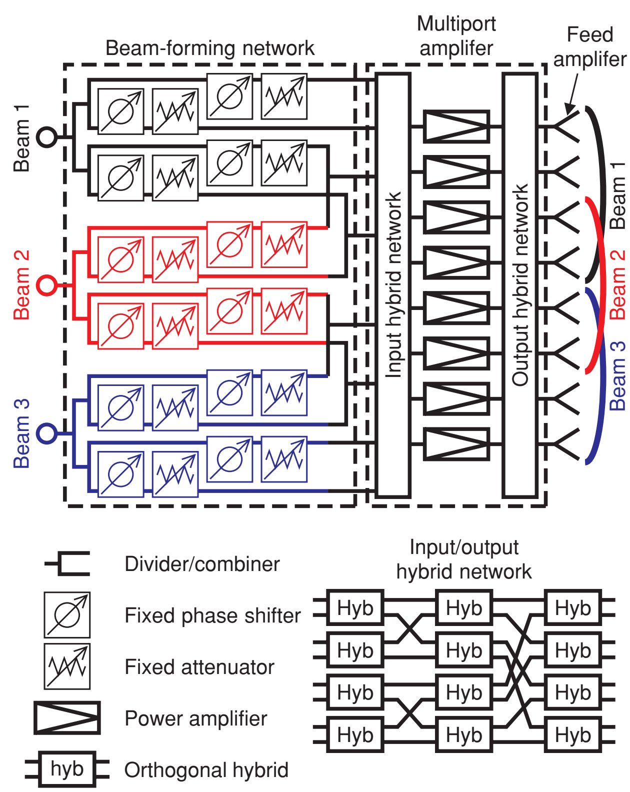


Fig. 3. Block diagram of a multibeam antenna feed system for a focal-feed-type antenna.

One possible beam allocation model uses 69 beams in 3-beam clusters. Each beam offers at least 52.9 dBW as its edge of coverage (EOC) EIRP (equivalent/effective isotropically radiated power). The antenna gain is 43.5 dBi and the RF output is 9.4 dBW. Total RF output power is 600 W (27.8 dBW).

The onboard antenna system must allocate RF power to each beam according to the beam's traffic and it must be possible to concentrate the RF power of each beam up to the power flux density limit, i.e., 18% of the total RF system power.

3. Conventional multibeam reflector antennas and feed systems

A typical onboard multibeam antenna configuration is a reflector antenna with a multibeam feed system. Such configurations fall into two classes according to the location of the feeder (**Fig. 2**) [4]. This section describes the configurations and the problems of conventional feed systems.

3.1 Focal-plane array feed type

A system with the feeder at location (1) in Fig. 2 is a reflector antenna system because the energy transmitted from a feed element in the focal plane forms a plane wave whose direction corresponds to the feed position. In this feed type, hereinafter called the focal-feed type, the beam-forming network (BFN) uses multiple elements around the focal position. A block diagram of a multibeam antenna feed system for a focal-feed-type antenna is shown in **Fig. 3**. This example shows a 3-beam system with 8 elements, where each beam is formed by 4 elements.

When we implement the power distribution function between beams, one option is a multiport amplifier (MPA) system [5]. This is because in the assignment of the required RF power, each beam input signal level is proportional to the RF power and the excited RF power of each feed element depends on the RF power distribution. The MPA can make the operating conditions of the high-power amplifiers (HPAs) independent of the RF power allocation of each beam input level. Unfortunately, the MPA needs a lot of hybrid circuits before and after the HPAs, as shown in Fig. 3. There are three problems with using an MPA.

1) The circuit scale of the hybrid matrices increases drastically with the number of input/output terminals.
2) The insertion losses of the output hybrid matrix suppress the effective antenna gain.
3) Since the output hybrid matrix must handle large RF power, it is much heavier than the input matrix.

3.2 Off-focal-plane array feed type

In the off-focal-plane-feed-type (hereinafter, off-focal-feed) reflector antenna, the array feeder is located in front of the focal plane at (2) in Fig. 2. The array feeder converts the wavefront at the array aperture to form the beam. Therefore, all elements are basically used for beam forming and must be controlled via the appropriate amplitude and phase weights. A block diagram of this type of antenna feed system is shown in **Fig. 4**. Although this type needs a large number of power dividers/combiners, fixed phase shifters, and fixed attenuators, the required RF power that needs to be handled before the HPA is small. Therefore, they can be effectively integrated as monolithic microwave integrated circuit devices [6].

In contrast to the focal feed type, this feed system can eliminate the input/output hybrid networks of the MPAs. Since all beams can share the same set of amplitude weights, the excited RF power of each feed element, p_i, does not depend on the RF power distribution, as shown by the following equation [7].

$$p_i = g_i \sum_{j=1}^{n} t_i a_{ij}^2 = g_i a_i^2 \sum_{j=1}^{n} t_j = g_i a_i^2 \qquad (1)$$

$$(a_{i1} = a_{i2} = \cdots = a_{ik} = a_i),$$

where g_i, t_j, and a_{ij} indicate the *i-th* HPA gain, the RF power distribution ratio of the *j-th* beam versus the total radiation output, and the amplitude weight of the *j-th* beam of the *i-th* feed element, respectively.

3.3 Issues for 100-beam-class feed systems that use conventional feed systems

Conventional feed systems are summarized in **Table 1**. The best approach to making a lightweight 100-beam-class feed system is to dispense with the MPA. Therefore, with respect to the issue of weight, the off-focal feed type has a big advantage over the focal feed type. However, the key problem with the off-focal-feed type is the low antenna gain. It is about 1–2 dB lower than that of the focal-feed-type antenna because of spillover and imperfect conversion of the wavefront. However, it does satisfy many of the other performance requirements, such as power distribution and lightweight. Therefore, we devised novel off-focal-feed-type-based antenna feed systems with improved antenna performances.

4. Multibeam antenna feed system using beam groups

4.1 Concept of beam groups

In the off-focal-feed-type antenna, the antenna gain decreases in proportion to its deviation from the gain optimal weight. Using the same set of amplitude weights allows the MPA to be dispensed with at the

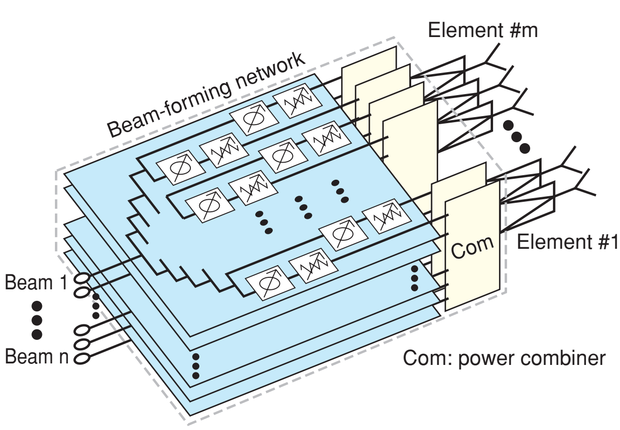


Fig. 4. Block diagram of a multibeam antenna feed system for an off-focal-feed-type antenna.

Table 1. Summary of conventional multibeam antenna feed systems.

Configuration (array position)	Focal feed	Off-focal feed
BFN	Simple	Complex
HPA system	MPA	Only HPA
Effective antenna gain*	Baseline	Less than 1–2 dB
Weight	Heavy	Baseline

* Includes insertion loss (2.0 dB) of output network.

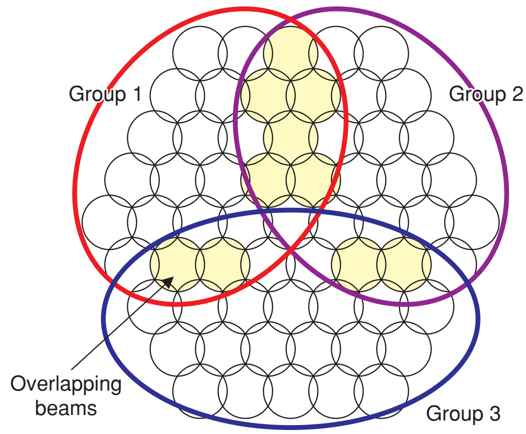


Fig. 5. Example of beam groups and overlapping beams.

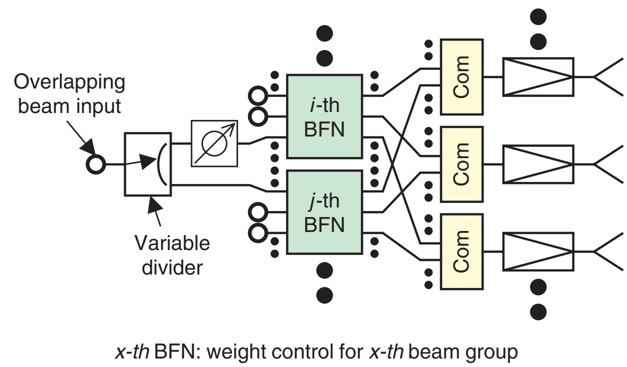


Fig. 6. Block diagram of our multibeam antenna feed system.

cost of an increase in amplitude weight error and a decrease in gain.

We focused on the properties of off-focal-feed-type antennas and calculated several sets of amplitude weights, each of which forms a beam group. In each beam group, all beams are excited by a common set of amplitude weights. Since each beam group contains beams that overlap ones in neighboring groups, as shown in **Fig. 5**, the deviation of the amplitude from the optimum value can be lowered.

How the RF power is excited is the key to eliminating the MPA. In the case of two beam groups, based on our design concept, the excited RF power of each element is given by

$$p_i = g_i \sum_{j=1}^{n} t_i a_{ij}^2 = g_i \left(A_{i1}^2 \sum_{j=1}^{k} t_j + A_{i2}^2 \sum_{j=k+1}^{n} t_j \right) \tag{2}$$

$$(a_{i1} = \cdots = a_{ik} = A_{i1}), (a_{ik+1} = \cdots = a_{in} = A_{i2}).$$

To keep p_i constant, we introduce a constraint such that for each beam group, the subtotal RF powers $\sum_{j=1}^{k} t_j$ and $\sum_{j=k+1}^{n} t_j$ are fixed. Thus, the MPA is not necessary in this feed system given this constraint.

4.2 Method for determining amplitude weights for beam groups

The amplitude weights for each beam group are determined by the following procedures.

1) Calculate the gain margin for the demands assuming that each beam is excited using the gain-optimal weight.
2) Find permissible amplitude weight errors corresponding to each beam's margin.
3) Calculate a set of amplitude weights A_{il} that satisfies 1) and 2) above.

This can maximize the average gain among beams while minimizing the antenna gain variance. Our scheme achieves higher antenna gain over the entire coverage area than is possible with a conventional off-focal-feed reflector antenna excited with the same set of amplitude weights.

4.3 Beam-forming technique for overlapping areas

Our technique offers good antenna characteristics while eliminating the MPA. However, it does restrict the flexibility of RF power distribution and the maximum assigned power because the RF power allocated to each beam group must be fixed. To solve these problems, we set beams (hereinafter called overlapping beams) that belong to two or more beam groups, as shown in Fig. 5. This configuration increases the power distribution flexibility of the overlapping beams while holding constant the subtotal power of each beam group.

A block diagram of a feed system that supports overlapping beams with the minimum number of additional devices is shown in **Fig. 6**. Here, the *i*-th and *j*-th BFN control phase and amplitude of each element correspond to beam groups #*i* and #*j*, respectively. The signals in the overlapping beams are appropriately divided by a variable divider. The divided signals are then input to the BFN ports that correspond to the area from which beams are radiated. The overlapping beams are formed by the spatial combination of the radiated beams. In this case, it is necessary to adjust the phase of each beam appropriately.

5. Antenna design for broadband scalable mobile communication satellite

This section describes the design of an onboard antenna for a broadband scalable mobile communication satellite that uses our beam-group concept.

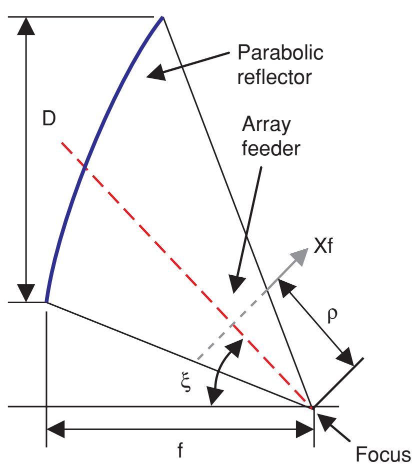
5.1 Antenna design

We designed an onboard multibeam reflector antenna that uses our new feed system and meets the expected system requirements. Antenna performance is greatly dependent on the number of beam groups: EOC gain increases in proportion to the number of beam groups. The flexibility of RF power distribution and the maximum assigned power both fall as the number of beam groups increases.

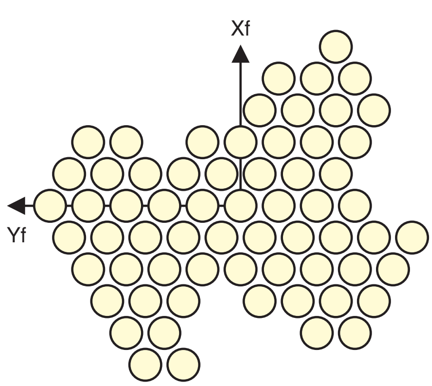
The antenna configuration is shown in **Fig. 7** and the antenna parameters are shown in **Table 2**. To minimize the amount of onboard equipment, the number of feed elements and the number of beams accommodated in beam group were restricted to powers of two. Design results for 3 beam groups and 11 overlapping beams are shown in **Fig. 8**. The subtotal RF power values of beam groups A, B, and C were 40%, 40%, and 20% of the total RF system power, respectively. We confirmed that this scheme can radiate sufficient RF power. The sum of the subtotal RF powers allocated to the beam groups can be assigned to the corresponding overlapping beams. For example, 80% of the total RF system power can be assigned to each overlapping beam between groups A and B. Therefore, the overlapping beams will normally be allocated to the main island of Japan because that area is expected to have the heaviest traffic.

5.2 Evaluation of antenna performances

To evaluate the performance of our antenna design, we examined a 69-beam antenna with different struc-



(a) Antenna configuration



(b) Feed element layout

Fig. 7. Designed multibeam reflector antenna.

Table 2. Antenna parameters.

Frequency	2.50 GHz
Aperture diameter: D	19.0 m
Focal length: f	13.3 m
Defocus length: ρ	1.2 m
Offset angle: ξ	43.5°
Feed element	Microstrip patch
Feed element spacing	120 mm
Number of elements	64
Number of beam groups	3 (A: 32, B: 32, C: 16)
Number of overlapping beams	11

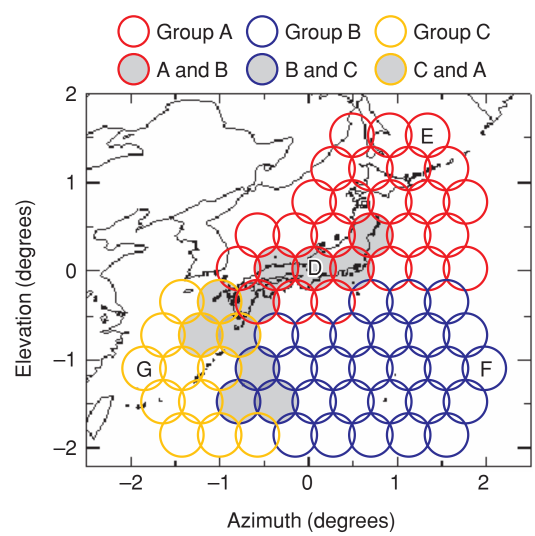


Fig. 8. Example of beam groups and overlapping beams.

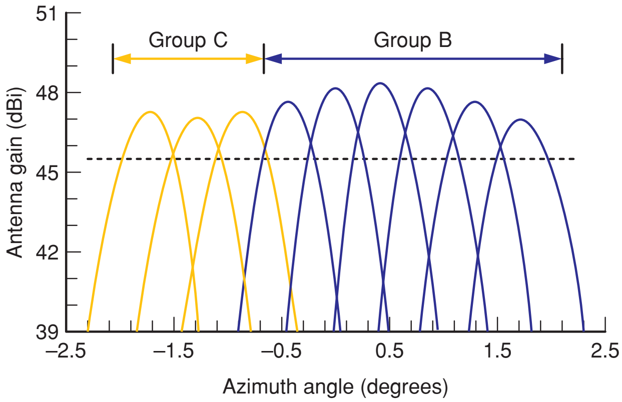
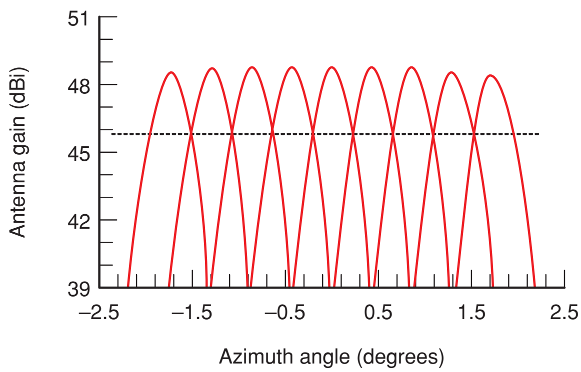
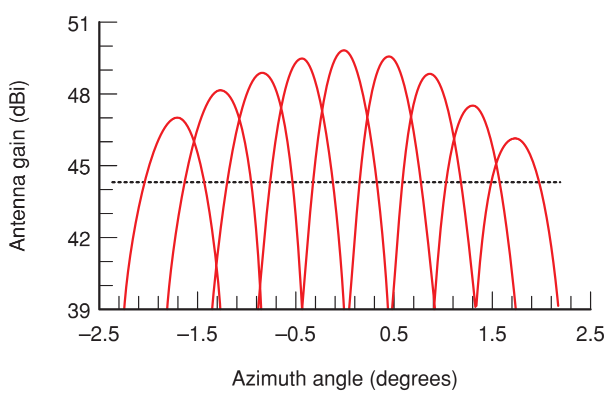


Fig. 9. Calculated antenna patterns for our feeder.



(a) Focal feeder with MPA



(b) Off-focal feeder with the same amplitude weights

Fig. 10. Calculated antenna patterns with conventional feeders.

tures. To provide a benchmark, we evaluated a multi-beam reflector antenna with conventional feed systems. We assumed the same reflector aperture diameter as for our antenna. In the focal array feed configuration, each beam was formed by seven elements and the amplifier part was assumed to consist of three 23-beam MPAs to achieve the required RF power concentration. MPA output loss was estimated to be 1.5 dB.

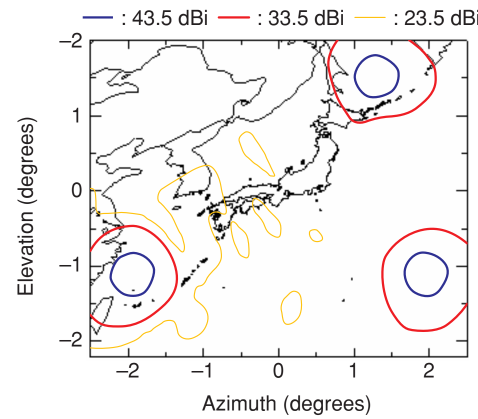


Fig. 11. Example of calculated antenna beam patterns. (Areas: E, F and G, contours: 43.5, 33.5, and 23.5 dBi)

Some examples of calculated antenna patterns are shown in **Figs. 9** and **10**. They correspond to the azimuth cut patterns (elevation angle: –0.7°) of 9 beams in Fig. 8. In these figures, the dotted lines show the minimum EOC gain of the 9 beams. Our new feed system offers the same minimum EOC gain as the focal-feed system; it has larger gain than the off-focal-feed system with the same amplitude weights. The minimum EOC gains of all 69 beams with our new feed system and the conventional focal feed system are 43.92 and 44.27 dBi, respectively. To evaluate the sidelobe characteristics, we calculated contour patterns of the south-west, south-east, and north-east edges (**Fig. 11**). Contours for 43.5, 33.5, and 23.5 dBi (only the south-west edge) are plotted. These calculations confirm that the antenna requirements are satisfied and that our scheme yields almost the same EOC gain as the conventional focal feeder.

We also calculated the antenna patterns of the overlapping beams. **Figures 12(a)**, **(b)**, and **(c)** show the antenna patterns formed with the group A amplitude weights, group B amplitude weights, and combined A + B weights, respectively. The gain deviation against power division ratio (d) of groups A and B covers the range from d = 0.0 (Group A) to d = 1.0 (Group B), as shown in **Fig. 13**. These results confirm that the overlapping beams meet all the expected requirements.

To determine the power distribution flexibility among beams, we calculated the RF power shortage due to HPA saturation; the virtual power distribution ratios were generated at random. The probability of power shortage, as determined from 1000 trials, is shown in **Fig. 14**. For comparison, the characteristics obtained with the conventional focal feeder using 3 MPAs and the case of not using overlapping beams are also shown in the figure. Because increasing the RF power shortage reduces the flexibility of RF power distribution among the beams, the results confirm that our new technique greatly improves the RF power distribution flexibility among beams.

Finally, we compared the weight of the conventional focal feed system and our new feed system; we considered the elements forming the feed systems shown in **Table 3**. Weights of the basic circuits were taken from previous reports [8]-[10]. Our new feed system offers almost the same performance as the

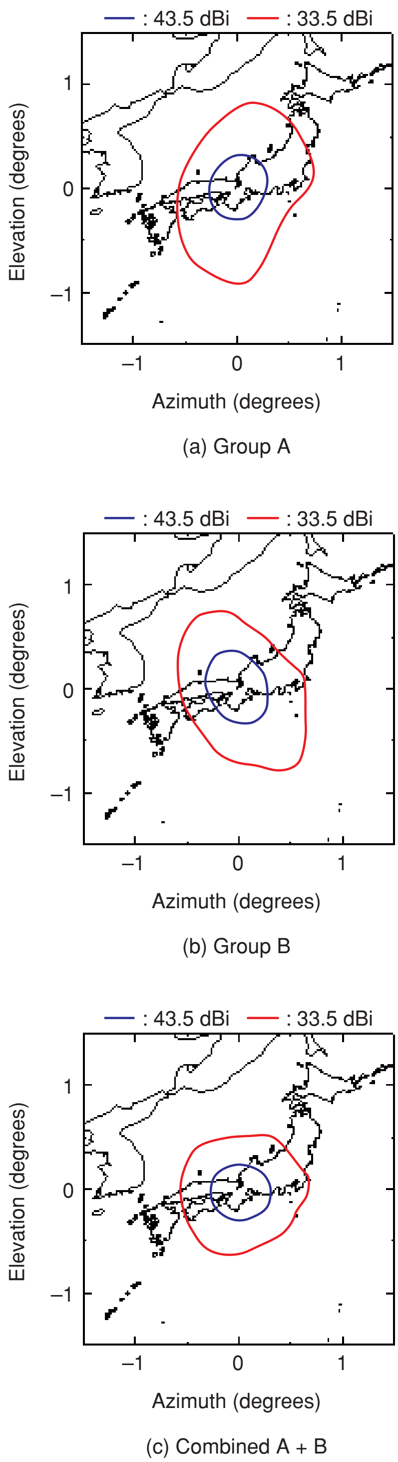


Fig. 12. Example of calculated antenna beam patterns (Area: D, contours: 43.5 and 33.5 dBi).

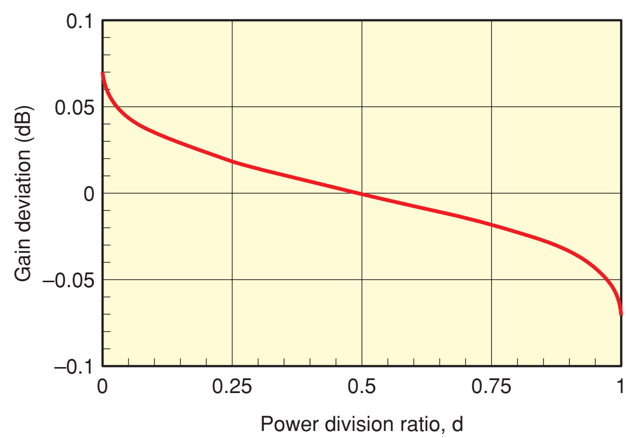


Fig. 13. Calculated coverage gain deviation versus power division ratio.

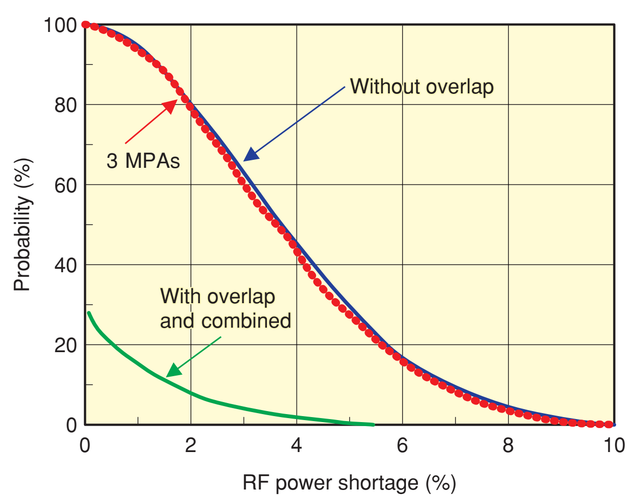


Fig. 14. Calculated RF power shortage against virtual power distribution.

Table 3. Comparison of components and weights of feed systems.

Configuration	Unit weight	Number of items	
		Focal feeder with MPAs	New feeder
Feed element	0.15	104	64
Hybrid for output hybrid network	0.3	192	0
HPA	1	104	64
BFN and Hybrid for input hybrid network for focal feeder	10	1	—
BFN for new feeder	30	—	1
Total weight	—	187.2	103.6

(units: kg)

focal feed system with an MPA but it weighs much less.

6. Conclusion

We investigated two novel techniques—a multi-beam antenna feed system that uses the beam-group concept and a beam-forming method that combines beams from different beam groups—for a lightweight onboard multibeam antenna feed system that offers RF power distribution among beams. Our beam-group concept improves the antenna gain over the entire coverage area compared with the conventional array-fed reflector antenna. Our beam-forming method combines beams from different beam groups and so improves the RF power distribution flexibility among beams.

We confirmed the validity of these methods by calculating antenna patterns for a 69-beam antenna. The antenna patterns formed by our feeder satisfy the antenna performance requirements. Weight estimations showed that our multibeam antenna feed system is much lighter than the equivalent conventional multibeam antenna feed systems while still satisfying the antenna performance requirements.

References

[1] M. Ueba, K. Ohata, and J. Mitsugi, "Next-generation Broadband Mobile Satellite Communication System in the Ubiquitous Network Era," NTT Technical Review, Vol. 5, No. 1, pp. 34-44, 2007.
[2] K. Nakahira, K. Kobayashi, and M. Ueba, "Resource Management and QoS Control Scheme in a Multibeam Satellite Communication System," NTT Technical Review, Vol. 5, No. 1, pp. 45-51, 2007.
[3] S. Harada, A. Meguro, and M. Ueba, "Tendon-reinforced Ultralight Large Antenna Reflector," NTT Technical Review, Vol. 5, No. 1, pp. 70-77, 2007.
[4] R. J. Mailloux, "Phased Array Antenna Handbook," Artech House, 1994.
[5] S. Egami and M. Kawai, "An Adaptive Multiple Beam System Concept," IEEE Journal on Selected Areas in Communications, Vol. SAC-5, No. 4, pp. 630-636, May 1987.
[6] T. Ohira, Y. Suzuki, H. Ogawa, and H. Kamitsuna, "Megalithic Microwave Signal Processing for Phased-Array Beam Forming and Steering," IEEE Trans. on MTT, Vol. 45, No. 12, pp. 2324-2332, Dec. 1997.
[7] K. Tokunaga, H. Tsunoda, H. Shoki, and M. Okumura, "Design Optimization of Phased Array Fed Reflector Antennas for Mobile Communication Satellites," 17th AIAA ICSSC, AIAA-98-1223, pp. 105-109, Feb. 1998, Yokohama, Japan.
[8] K. Ueno, M. Atobe, T. Ide, Y. Suzuki, and M. Okumura, "ETS-VIII S-Band Antenna Feed System and Electrical Properties," Proc. of the International Symposium on Space Technology, Bibliographic details 2000, Vol. 22ND/2, pp. 1493-1498, 2000.
[9] F. Ishitsuka, N. Iwasaki, T. Ohira, Y. Suzuki, and Y. Ando, "A compact three-dimensional packaging technique using super-fine-pitch coaxial connector arrays for on-board satellite equipment," IEEE Transactions on Advanced Packaging, Vol. 23, No. 3, pp. 530-537, Aug. 2000.
[10] http://www.mitsubishielectric.co.jp /society/space/

Yoshinori Suzuki

Research Engineer, Satellite Communication Systems Group, Wireless Access Systems Project, NTT Access Network Service Systems Laboratories.

He received the B.E. in communication engineering, the M.E. and Ph.D. degrees in electrical and communication engineering from Tohoku University, Miyagi, in 1993, 1995, and 2005, respectively. He joined NTT Wireless Systems Laboratories in 1995. Since then, he has been engaged in R&D of multibeam antenna feed systems for communication satellites. He is currently working on future mobile satellite communication systems. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Akira Meguro

Associate Senior Engineer, Engineering Test Satellite VIII Project, Japan Aerospace Exploration Agency (JAXA), Office of Space Applications.

He received the B.E. and M.E. degrees in mechanical engineering from Keio University, Tokyo, and the Ph.D. degree in aerospace engineering from the University of Tokyo, Tokyo, in 1983, 1985, and 2004, respectively. He joined NTT in 1985. His main field is R&D of spacecraft structures. In particular, he has been studying large deployable antenna reflectors on board communication satellites. He has worked for several satellite projects such as ETS-VI, VSOP, N-Star c, and ETS-VIII. He moved to Japan Aerospace Exploration Agency in 2006.

Kiyoshi Kobayashi

Senior Research Engineer, Supervisor, Satellite Communication Systems Group, Wireless Access Systems Project, NTT Access Network Service Systems Laboratories.

He received the B.E., M.E., and Ph.D. degrees in electrical engineering from Tokyo University of Science, Tokyo, in 1987, 1989, and 2004, respectively. He joined NTT Radio Communication Systems Laboratories in 1989. Since then, he has been engaged in R&D of digital signal processing algorithms and their implementation techniques including modulation/demodulation, synchronization control, and diversity for satellite and personal wireless communication systems. He is currently working on future mobile satellite communication systems. He is a member of IEEE and IEICE.

Masazumi Ueba

Senior Research Engineer, Supervisor, Group Leader, Satellite Communication Systems Group, Wireless Access Systems Project, NTT Access Network Service Systems Laboratories.

He received the B.E. and M.S. degrees in aeronautical engineering, and the Dr.Eng. degree for work on the design methodology of highly accurate antenna pointing system from the University of Tokyo, Tokyo, in 1982, 1984, and 1996, respectively. He joined the Yokosuka Electrical Communication Laboratories of Nippon Telegraph and Telephone Public Corporation (now NTT) in 1984. He has been engaged in research on the dynamics of antenna pointing control systems of satellites and shape control systems for large antenna reflectors. He is currently researching technologies for next-generation mobile satellite communication systems. He is a member of IEICE, the Japan Society for Aeronautical and Space Sciences, and the American Institute of Aeronautics and Astronautics.