Resource Management and QoS Control Scheme in a Multibeam Satellite Communication System

Katsuya Nakahira†, Kiyoshi Kobayashi, and Masazumi Ueba

Abstract

To develop large-capacity, high-quality mobile satellite communication systems in the future, we will need to use a multibeam scheme that uses extremely high levels of frequency reuse. In this article, we describe a resource allocation algorithm for multibeam satellite communication systems that can dynamically adapt to the maximum communication capacity without compromising quality, thus enhancing the quality of service (QoS). The algorithm combines two resource allocation schemes that enable it to cope with ever-changing user distributions and interbeam interference conditions.

1. Introduction

Mobile Internet services on terrestrial cellular networks are currently available only in densely populated areas. There is, however, a fairly large demand for them outside these areas. Mobile satellite networks can meet these demands because satellites are the most efficient means for reaching rural and remote areas using high-speed, ubiquitous links.

Based on our estimation of market demand, the next-generation mobile satellite system [1] will need to have a capacity of 1 Gbit/s. A GEO (geostationary earth orbit) satellite with a very limited payload power (2 kW) will probably be used because of its low capital investment requirements. Unfortunately, the S-band, which is usually assigned to mobile satellite services, has a very limited frequency bandwidth of 35 MHz. To obtain a large capacity from limited resources, such as bandwidth and payload power, we must utilize a multibeam system that allows extremely high levels of frequency reuse [2]. However, in multibeam systems, interbeam interference reduces the communication capacity and link quality. In mobile communication systems, there are usually large fluctuations in user distribution, depending on time and geographical area. Thus, beam traffic is uneven in the service area. Unfortunately, such uneven traffic reduces communication capacity because a high-traffic beam tends to require higher power, so it interferes more with the other beams. Consequently, to provide high-capacity services while maintaining high-quality communications, we should ensure that system resources are meticulously assigned to each user within each beam.

This article describes novel resource allocation schemes that enable mobile satellite systems to cope with the ever-changing user distribution and interbeam interference conditions. The schemes focus on a forward link that needs an extremely large capacity. To simplify the resource allocation while maintaining high capacity and high quality, the scheme's algorithm combines two resource allocations, by linking among beams and within a single beam. The first scheme optimizes the resources among beams to minimize interference. The second scheme manages the various required resources and adapts them to the beam gain and interference levels at various user locations within a single beam. These schemes are layered, can allocate multibeam satellite resources to cope with the increasing communication demand, and improve the communication quality, thus enhancing QoS.

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

2. Multibeam configuration

In the multibeam satellite system, the Japanese economic zone is covered by 69 beams, as shown in **Fig. 1**. For greater usable frequency bandwidth, the frequency of each beam must be reused to avoid overlaps between contiguous beams. To construct one three-beam cluster, we divide system bandwidth *Wsys* into three frequency areas: F_1, F_2, and F_3. The boundaries of these areas vary depending on the resource allocation scheme, as described below.

The system supports a wide range of applications, from data telemetry to broadband services. Thus, the transmission bit rate of the user terminal needs to be from 1 kbit/s to 100 Mbit/s. One characteristic of mobile communication systems is that users are distributed non-uniformly in the service area. For simplicity, we assumed beams of identical shape, a parabolic satellite antenna, and radially symmetrical gain, as shown in **Fig. 2**. The side-lobe of one beam has considerable influence on the other beams; hence, interference from the adjacent beams diminishes communication capacity and quality. The beam edge gain is set at the most general value for antenna architecture: –3 dB relative to the beam center.

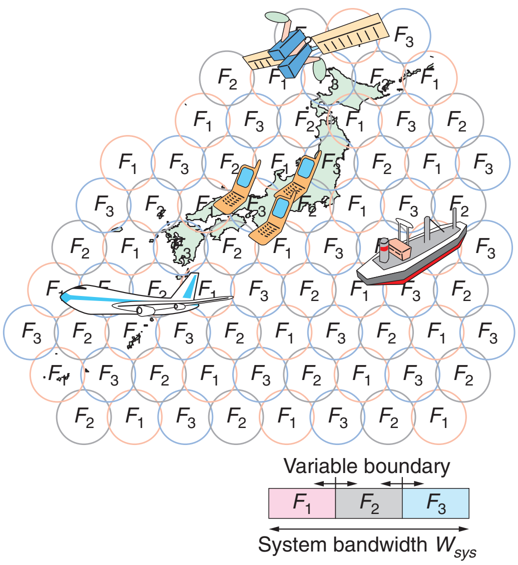


Fig. 1. Multibeam satellite communication system.

3. Resource allocation

In conventional multibeam systems, for easy allocation of resources while maintaining high efficiency, *Wsys* is assigned to all beams that use CDMA (code division multiple access) [3], [4]. Such systems only adapt the satellite's transmission power depending on the beam traffic. However, in the CDMA system, it is difficult to achieve our goal capacity of 1 Gbit/s while keeping up with the uneven beam traffic, because a high traffic beam requires very high power compared with other systems such as ones based on FDMA (frequency division multiple access) systems. Such high power causes more interference with the other beam.

In this way, we have proven that V-FDMA (variable FDMA) with power adaptation is more effective at enhancing communication capacity [5]. Therefore, the resource allocation scheme simultaneously varies the frequency bandwidth and power depending on the user distribution.

As shown in **Fig. 3**, we assumed that the users' equipment uses adaptive modulation. In adaptive

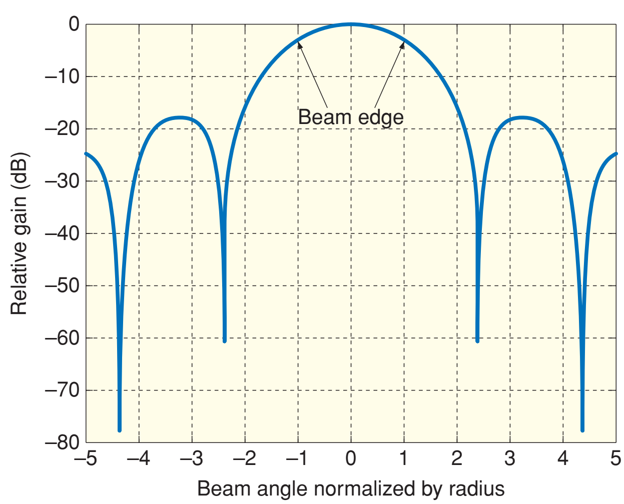


Fig. 2. Satellite antenna beam pattern.

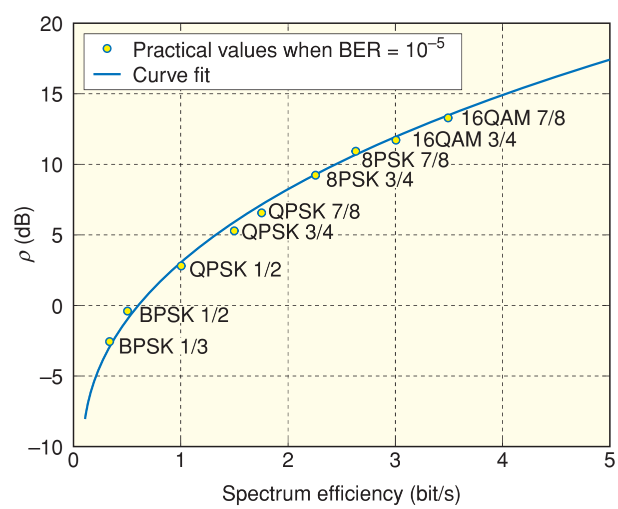


Fig. 3. Adaptive satellite modem performance.

modulation, a spectrum efficiency η, determined by the forward error correction coding rate and the number of modulation levels, is appropriately chosen from the received power ratio ρ, which is defined by

$$\rho = C/(N + I), \quad (1)$$

where C is the carrier power, N is the thermal noise, and I is the interbeam interference.

This section describes a combination of two resource allocation schemes. One involves allocating resources among the beams to achieve the lowest possible interbeam interference and the other involves allocating resources within a single beam to adapt to the user's location. Both schemes are layered to increase communication capacity and improve communication quality.

3.1 Resource allocation among beams

Excessive beam power increases interbeam interference, and as a result, reduces total communication capacity. Therefore, the main purpose of the scheme is to determine the beam bandwidth that will best minimize the total transmission beam power, thus minimizing interference. For this purpose, we applied the most promising optimization programming technique, SQP (sequential quadratic programming) [6], to adjust the bandwidth and power. However, it is still difficult to properly adjust these resources, and there are a lot of dependent optimization parameters.

To simplify the problem while minimizing interference, we introduce new constraints for the optimization. In general, the power can be minimized by using the lowest spectrum efficiency. This is because the lower the spectrum efficiency, the lower the power, as shown in Fig. 3. To lower the spectrum efficiency while retaining the frequency reuse pattern, we apply the following two new constraints on bandwidth to SQP.

(1) Three beams in any cluster should use up the system frequency bandwidth and
(2) Each beam in the same frequency area should have the same frequency bandwidth.

As shown in **Fig. 4**, using no constraints, which allows narrow or overlapping frequency bandwidth beams, requires more power, and thus increases interference. Conversely, by using constraints, we can avoid the previous bandwidth allocations, such that constraint (1) widens the frequency bandwidth up to the system limit and constraint (2) never causes overlapping of the bandwidth for any of the beams.

In addition, the number of optimization parameters can be dramatically decreased from 69 to 2 because only two frequency boundaries need to be optimized in a 3-beam cluster. Generally, reducing the parameters is highly effective at avoiding the local minimum solution. Therefore, the clarified constraints can achieve the lowest interference. We call this scheme ORA (optimal resource allocation) for the multibeam system.

3.1.1 Performance of ORA

Since a single beam can cover a densely populated area such as Tokyo, we assumed an unequal traffic pattern in which one single beam had heavy traffic while the other beams had very little. From this assumption, we define a traffic concentration ratio T_r as being when the heavy-traffic beam has T_r times the traffic of the other beams.

The results of the resource allocation using ORA with $T_r = 5$ are shown in **Fig. 5**. The x-axis is the beam number when beam 1 has heavy traffic. As can be seen from the constraints, Fig. 5(a) shows that beams in the same frequency areas are allocated the same bandwidth, while beams within a cluster use up the system bandwidth. Hence, the total bandwidth of beams 1, 2, and 3 is 35 MHz. As shown in Fig. 5(b), the power density of each beam is allocated to carry unequal traffic simultaneously.

3.2 Resource allocation within a beam

Resource allocation among the beams as clarified above did not take into account individual user requirements, such as the receiver antenna size and radio propagation due to inner-beam location. This

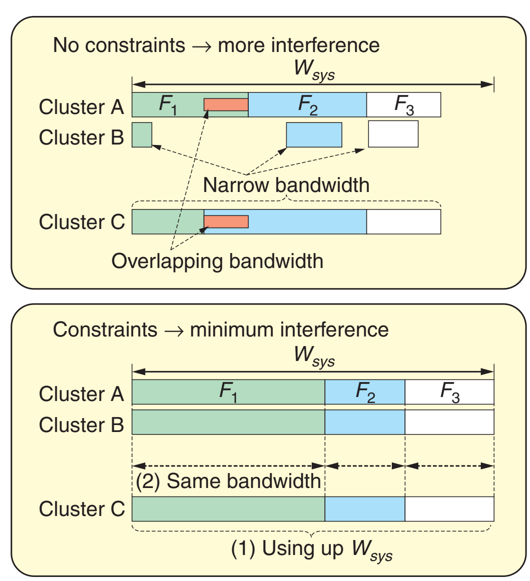
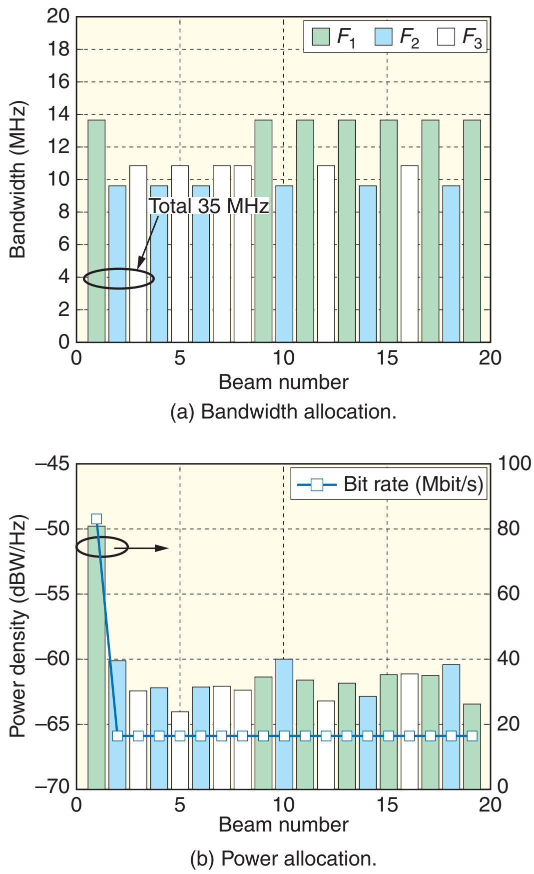


Fig. 4. Bandwidth constraints for the optimization algorithm.

section describes how to manage the differences among users located in the inner-beam area.

The beam gain and interference levels change depending on the location within the inner beam. Thus, depending on their locations, users should be allocated resources to provide required bit rate *Rreq* and required *ρreq*, given as the prescribed communication quality, such as BER (bit error rate).



(a) Bandwidth allocation.

(b) Power allocation.

Fig. 5. Optimal resource allocation among beams at $T_r = 5$.

For individual users, bandwidth W, power density P_r, and spectrum efficiency η can generally be chosen as parameters. However, because W is determined by $Rreq/\eta$, those can be reduced to two parameters, P_r and η. From these, two resource allocation schemes can be proposed:

(1) Variable P_r with fixed η for a variable power density (VPD) and

(2) Variable η with fixed P_r for a fixed power density (FPD).

3.2.1 Variable power density

Since the beam gain and interference levels change within a beam, ρ is estimated for the user's location as shown in **Fig. 6**. Thus, the VPD varies P_r to satisfy the requirement for ρ while factoring in the inner-beam location. VPD then sets an identical η for all users in a beam. However, such P_r differences cause the following problems.

As shown in **Fig. 7(a)**, users *a* and *c* are allocated a

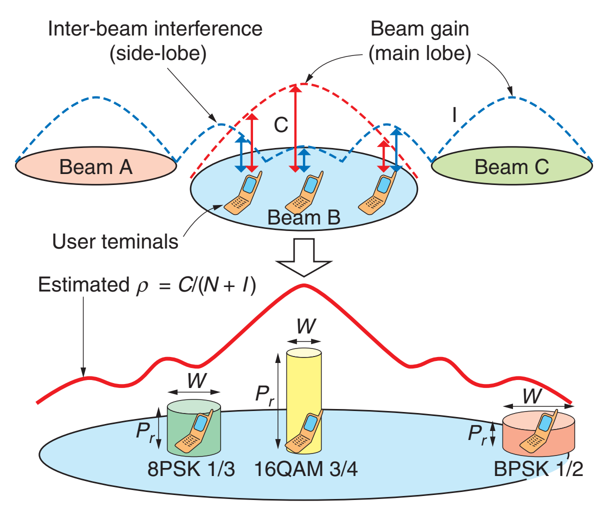


Fig. 6. Radio propagation within a beam.

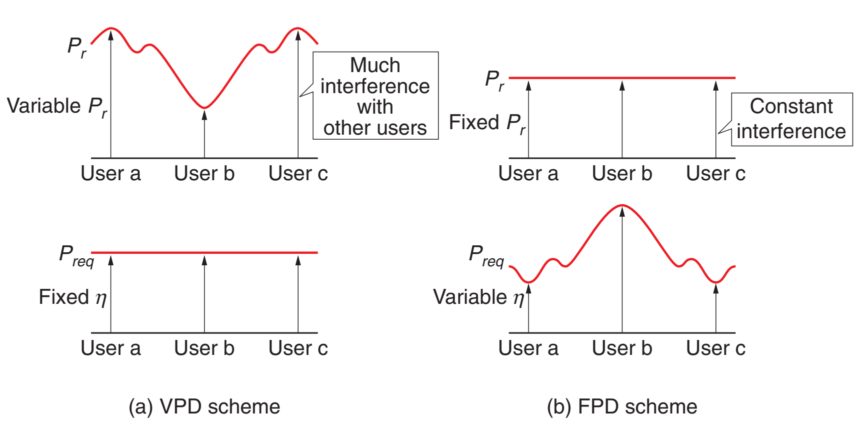


Fig. 7. Resource allocation within a beam.

higher power density than user *b* because of the smaller beam gain. Thus, the users of other beams located in the beam center experience more interference if they are allocated the same power as *a* or *c*. In other words, interference changes depending on frequency, so the received power ratio sometimes falls below ρreq.

3.2.2 Fixed power density

As shown in **Fig. 7(b)**, to enable the problem that arises using VPD to be overcome, FPD keeps P_r constant within the beam while adjusting η to the user's location. Therefore, the allocated power depends on only the bandwidth because the power density remains constant. Thus, when $Wsys$ is used up, the interference density for one user is independent of the assigned frequency. Consequently, interference fluctuations, such as those in VPD do not occur.

3.3 Two-layer resource allocation

A two-layer allocation flow-chart is shown in **Fig. 8**. The first scheme allocates the resources among beams satisfying the beam traffic, and then the second scheme allocates the resources among beams depending on the various user locations.

Earlier, ORA was described for the first scheme and VPD and FPD were described for the second scheme. However, it should be noted that ORA determines η for each beam, even though FPD adjusts η for each user. Therefore, when FPD is used as the second scheme, the two-layer process is iterated to converge η for each beam [7].

FRA (fixed resource allocation) is added to the first scheme, which fixes 1/3 of the system bandwidth of all beams, while adjusting the power to satisfy the uneven beam traffic.

4. Performance of the resource allocation schemes

Finally, we evaluate the performance of the combination of the previously described schemes. We first evaluate the communication quality for each user and then evaluate the communication capacity in various traffic situations. The simulation parameters are summarized in **Table 1**.

4.1 Communication quality

VPD and FPD using ORA are compared in **Fig. 9** to show the difference between received ρ and ρreq for each user. They were calculated for beams 1 and 2 when the frequency was randomly selected for each user.

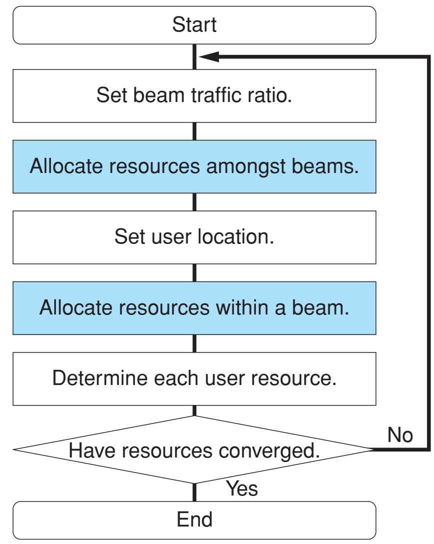


Fig. 8. Flow-chart of a two-layered resource allocation.

Table 1. Simulation parameters.

Beam number	69
System bandwidth W_{sys}	35 MHz
Satellite transmission power	600 W
User terminal G/T	–11.3 dB/K
Required BER	10^{-5}
Required bit rate R_{req}	1 Mbit/s
User location	Beam center or edge
Users in a low-traffic beam	10
Users in a high-traffic beam	$10 \times T_r$

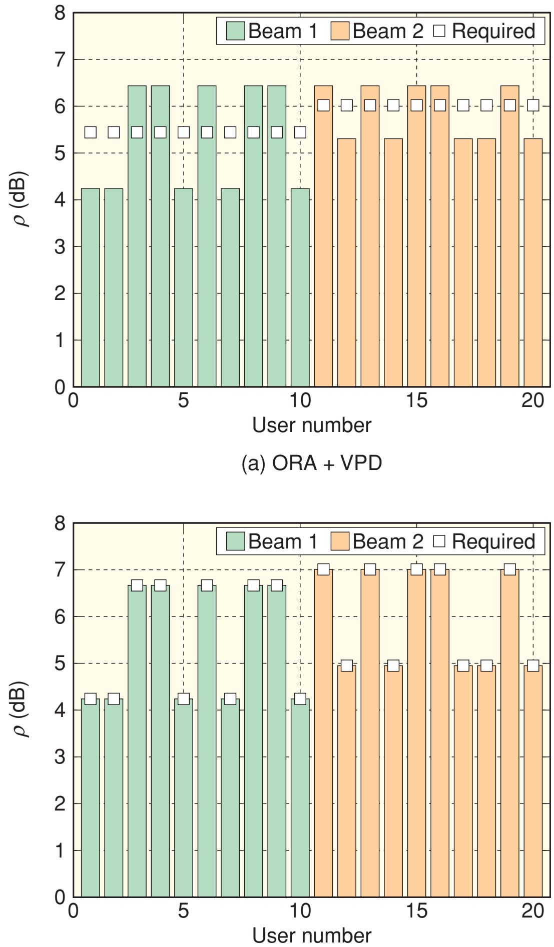
In the ORA + VPD shown in Fig. 9(a), some users who received ρ did not reach ρreq because of the large amount of interference generated by users who were allocated high power density, as previously mentioned. This consequently degraded communication quality.

However, in ORA + FPD, because the interference power density remained constant regardless of the frequency assignment, a stable ρ was supplied for the user locations shown in Fig. 9(b).

These results show that ORA + FPD can guarantee the prescribed communication quality for all users, meaning that it is superior to ORA + VPD in enhancing QoS.

4.2 Communication capacity

We examined the maximum communication capacities using up both the system bandwidth and satellite transmission power for the four different allocations.



(a) ORA + VPD

(b) ORA + FPD

Fig. 9. Received ρ and required ρ of each user.

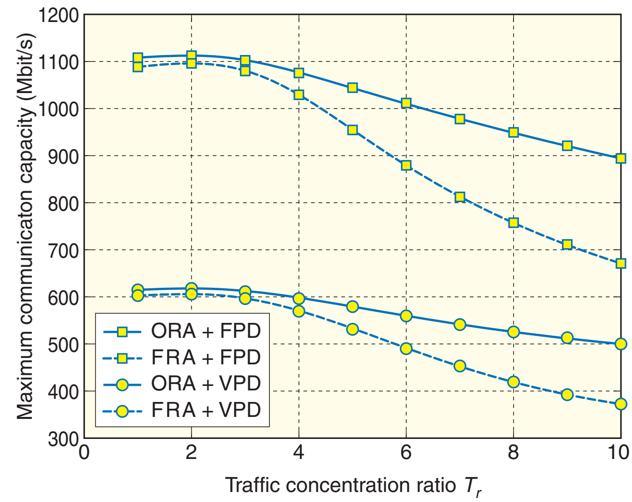


Fig. 10. Communication capacity.

Capacity was calculated by summing for users who received adequate ρreq. The results are shown in **Fig. 10**. The x-axis is traffic concentration ratio T_r when the users concentrate on the Tokyo beam.

The figure representing ORA + FPD shows that it offers higher capacities than the others when T_r is denser. Specifically, it achieves our goal: a capacity higher than 1 Gbit/s. Also, ORA + FPD has up to double the capacity that FRA + VPD has when $T_r \geq 7$ is applied. This is because FRA cannot cope with the varying traffic conditions because the bandwidth of each beam is fixed. However, ORA enhances the capacity by optimally coping with the bandwidth allocated to each beam. In addition, FPD enhances the capacities more than VPD, because VPD lowers ρ to below the expected value. As a result, some users do not reach ρreq.

Based on the evaluations in this section, it is clear that ORA + FPD both attained the prescribed communication quality and enhanced system capacity regardless of user distributions in multibeam systems. In this respect, resource allocation using ORA + FPD proved superior to the other allocation schemes.

5. Conclusion

This article described a resource allocation algorithm for multibeam satellite systems that can simultaneously control satellite resources, such as transmission power, frequency bandwidth, and modulation parameters, while factoring in interbeam interference and user location. The results demonstrate that applying an optimal algorithm under new constraint conditions can result in optimal solutions that minimize interbeam interference and offer better capacity than conventional systems.

Furthermore, the performance of allocation schemes that can cope with user locations by applying this optimal algorithm was analyzed, and the results showed that a fixed power density with adaptive modulation could guarantee communication quality independent of the center frequency allocation of the user bandwidth.

References

[1] M. Ueba, K. Ohata, J. Mitsugi, and M. Umehira, "Broadband and scalable mobile satellite communication system for future access network," AIAA-2004-3154, May 2004.

[2] Y. Nakasuga, J. Mitsugi, K. Ohata, and M. Ueba, "Communication Capacity Enhancement with Adaptive Resource Assignment for Multi-beam Mobile Satellite Communication Systems," AIAA-2004-3147, May 2004.

[3] J. Romero-Garcia and R. de Gaudenzi, "On Antenna Design and Capacity Analysis for the Forward Link of a Multibeam Power Con-

trolled Satellite CDMA Network," IEEE J. Select. Areas Commun., Vol. 18, No. 7, Jul. 2000.
[4] K. S. Gilhousen, I. M. Jacobs, R. Padovani, and L. A. Weaver, "Increased Capacity Using CDMA for Mobile Satellite Communication," IEEE J. Select. Areas Commun., Vol. 8, No. 4, May 1990.
[5] K. Nakahira, K. Kobayashi, K. Ohata, and M. Ueba, "A Study on an Optimal Resource Allocation Algorithm for Next Generation Mobile Satellite Communication Systems," Technical Report of IEICE, JC-SAT2004-351, Oct. 2004.
[6] R. Fletcher, "Practical Methods of Optimization," John Wiley and Sons, 1987.
[7] K. Nakahira, K. Kobayashi, and M. Ueba, "Communication Capacity and Quality Enhancement Using a Two-layered Adaptive Resource Allocation Scheme for Multi-beam Mobile Satellite Communication Systems," IEICE Trans. Commun., E89-A, No. 7, pp. 1930-1939, July 2006.

Katsuya Nakahira
Research Engineer, Satellite Communication Systems Group, Wireless Access Systems Project, NTT Access Network Service Systems Laboratories.
He received the B.S. and M.S. degrees in physical science from Kochi University, Kochi, in 1989 and 1991, respectively. Since beginning to work at NTT Radio Communications Systems Laboratories in 1991, he has mainly been engaged in research on satellite communication network management and the development of satellite earth station equipment. His current interest is a QoS architecture for mobile satellite communication systems.

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 the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

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.