Interference-Limited Dynamic Resource Management for an Integrated Satellite/Terrestrial System

Unhee Park, Hee Wook Kim, Dae Sub Oh, and Bon-Jun Ku

An integrated multi-beam satellite and multi-cell terrestrial system is an attractive means for highly efficient communication due to the fact that the two components (satellite and terrestrial) make the most of each other's resources. In this paper, a terrestrial component reuses a satellite's resources under the control of the satellite's network management system. This allows the resource allocation for the satellite and terrestrial components to be coordinated to optimize spectral efficiency and increase overall system capacity. In such a system, the satellite resources reused in the terrestrial component may bring about severe interference, which is one of the main factors affecting system capacity. Under this consideration, the objective of this paper is to achieve an optimized resource allocation in both components in such a way as to minimize any resulting inter-component interference. The objective of the proposed scheme is to mitigate this inter-component interference by optimizing the total transmission power — the result of which can lead to an increase in capacity. The simulation results in this paper illustrate that the proposed scheme affords a more energy-efficient system to be implemented, compared to a conventional power management scheme, by allocating the bandwidth uniformly regardless of the amount of interference or traffic demand.

Keywords: Integrated system, multi-beam satellite, terrestrial component, inter-component interference, resource allocation.

I. Introduction

One of the biggest issues in the area of information and communication is convergence. The desire for high-speed multimedia communication services that can be connected with anyone, anytime, and anywhere without the limitations of time and space has brought about an explosion in traffic demand. In addition, extensive coverage of mobile services can be accomplished through a wide range of wireless communication infrastructures. These changes in the telecommunication network environment are now leading existing systems to be gradually integrated with, or replaced by, new systems for the deployment of cost effective and flexible networks. In this paper, we focus in particular on integrated satellite/terrestrial systems.

A satellite repeater can not only cover broadband communication coverage but is also equipped with a multi-beam antenna that can support high data rates by projecting a high power density to each spot beam [1]. In addition, an earth station can be made smaller by developing RF technologies and using high frequencies. This, as well as advanced transmission techniques such as an adaptive modulation and coding (AMC) scheme, contribute to the provisioning of high-speed satellite multimedia services [2]. Accordingly, recent satellite systems aim at reinforcing their role as the main communication network and not as a complement to a terrestrial system.

Traditionally, mobile satellite service (MSS) systems can provide ubiquitous and reliable connectivity owing to their inherent wide coverage area. Their strengths in providing complementary coverage to terrestrial networks in areas where population densities cannot support the introduction of large-scale commercial land-based infrastructure have made mobile

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satellite systems an indispensable part of communication networks. On the other hand, no conventional MSS system has total penetration capability because of the excessive blockage and shadowing of satellite links in suburban and urban areas, including inside buildings. This fact means that current satellite operators suffer in terms of economic viability and economy of scale.

Therefore, the importance of integrated satellite/terrestrial systems has increased during the last few years in an effort to serve a range of new multimedia services in an efficient, secure, and cost-effective environment [3]–[4]. The purpose of this integration is the effective utilization of the respective advantages of each network within the context of their traditional roles and mandates.

In this paper, an integrated satellite/terrestrial system is evolved from traditional MSS networks into a single network that uses both satellite and terrestrial transmission paths to provide high-speed multimedia services. The terrestrial component is operated as an integral part of the MSS system and aims at improving the service coverage of the MSS system where the satellite component suffers from signal blockage by obstacles such as buildings. In addition, these terrestrial components are controlled by the satellite resource and network management system and use the same portions of MSS frequency bands in which the satellite component is operated. To support the kind of data rates that are widely based on the previously mentioned traffic growth and technology trends, the frequency resources need to be used effectively in both components. Therefore, research activities in such integrated systems as these are mainly focused on how to make more intelligent networking and more efficient use of the radio spectrum, such as in dynamic channel or spectrum allocation. Meanwhile, one of the major challenges that these types of integrated systems should overcome is how to minimize the inter-component interference that arises from satellite frequency reuse in terrestrial components. This inter-component interference within a single network leads to a consideration of a system's capacity and link quality.

In [5], a satellite intra system and terrestrial inter-component interference on a satellite uplink versus the number of active terrestrial users that obtain the service simultaneously is shown. It is noted that the most severe interference comes from the uplink signals of terrestrial users — this is because there is no blockage or shadowing over the link to the satellite and because they use the same uplink frequency as the considered satellite link. In addition, [5] emphasizes the smart channel-allocation policy to reduce the inter-component interferences. Also, these interference issues have been addressed [6] by North American satellite operators such as Skyterra, which has many patents aiming at avoiding or mitigating interference. In an effort to limit interference, the authors in [7] discussed the addition of an ancillary terrestrial component (ATC) to the network and the resulting integration problems. It is regarded that among the major challenges facing the use of an ATC with an MSS is the problem of interference; thus, an interference mitigation scheme using ground-based beamforming was proposed. In addition, the authors in [8] proposed the use of a radio resource management strategy in which the optimal constraint conditions are applied to minimize inter-beam interference for multiple beams based on satellite networks. In particular, an optimum frequency bandwidth and satellite transmission power scheme was proposed in [8] to deal with the ever-changing user distribution and inter-beam interference conditions.

Similar to this concept, we bring up an optimal interference constraint for an integrated MSS system to minimize severe interference between a satellite beam and terrestrial cells that are operated in the same frequency. We then propose a dynamic resource allocation scheme to mitigate the total inter-component interference by optimizing the total transmission power — the result of which can lead to an increase in capacity. Finally, we evaluate the performance of the total consumed power, the amount of inter-component interference, and the capacity with respect to different traffic distributions and interference environments between the satellite beam and terrestrial components.

II. Integrated Satellite/Terrestrial Systems

Figure 1 shows the system configuration of the integrated multi-beam satellite and multi-cell terrestrial network. In the network, for the efficient use of satellite frequency, a multi-beam–based satellite component introduces an ensemble of spot beams. A satellite antenna with a large-sized reflector allows a number of small spot beams to be formed. In addition,

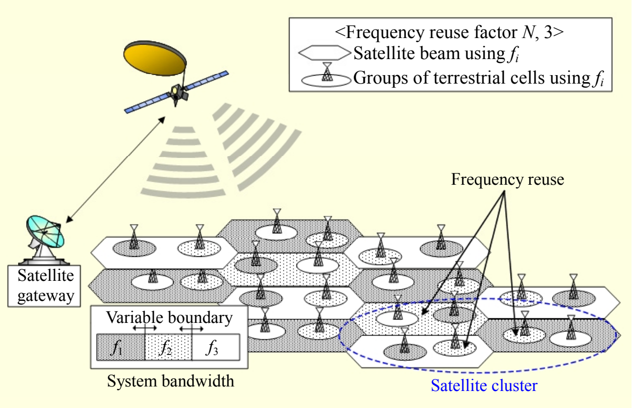

Fig. 1. Integrated multi-beam satellite/terrestrial system with frequency reuse.

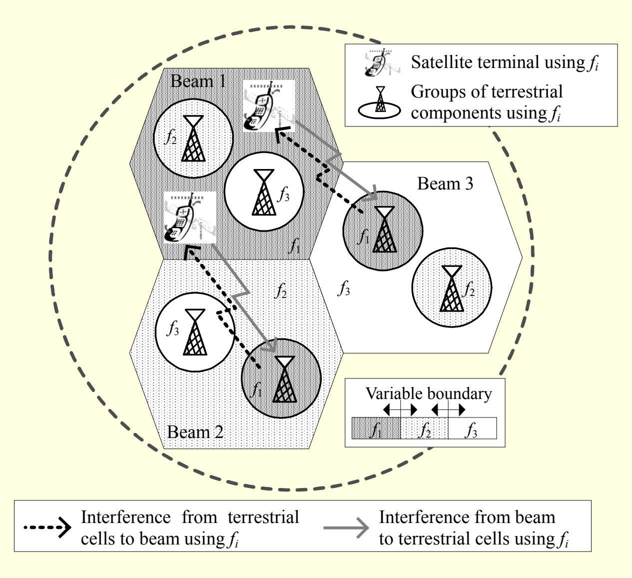

Fig. 2. Inter-component interference between satellite beam and terrestrial cells.

there are terrestrial components that can reuse the same portion of satellite frequency bands allocated in the satellite spot beams. This integrated network can benefit from the advantages of terrestrial cellular networks with the provisioning of high-capacity communication in suburban and urban areas, as well as the strong aspects of satellite networks with a wide area of coverage and rapid reconstruction capability. In this integrated system, the satellite and terrestrial components are controlled by a common resource management system that facilitates the coordination of frequency allocation between both components.

A satellite frequency reuse pattern for the terrestrial cells in an integrated MSS system is illustrated in Fig. 1. To provide a high degree of spectrum-utilization efficiency, the satellite frequency allocated for each spot beam can be reused in terrestrial cells outside the coverage of each spot beam but should not be reused within the spot-beam coverage owing to severe co-channel interference between the two components. In this paper, we assume the integrated MSS system based on a multi-beam satellite component with a cluster composed of three spot beams operating in different frequency bands f_1, f_2, and f_3 in a system with a frequency reuse factor (N) of three. The three frequency bands are not overlapped mutually within a cluster and are reused for three beams of any other clusters in the same manner. In addition, the terrestrial components are deployed with the reuse of the three frequency bands to improve the spectral efficiency in a high-density population area over the coverage of each satellite beam. In other words, the terrestrial components can reuse a frequency band which a satellite beam covering over them does not use. That is, a satellite beam and the terrestrial cells in the adjacent beam can share the same frequency band, but this simultaneous sharing of a frequency band will cause interference, as shown in Fig. 2. In this paper, we refer to this as the inter-component interference.

In Fig. 2, each spot beam and group of terrestrial cells of the same frequency contain the same graphical pattern. This illustrates the interference between the satellite beam with the closest groups of terrestrial cells that use the same frequency band, while belonging to contiguous beams. Since inter-component interference can degrade performance, it is essential to limit it. In this paper, we consider some constraint conditions from the concept described in [9] to mitigate the system interference and present a dynamic resource allocation scheme for integrated MSSs with a terrestrial component.

III. Dynamic Resource Allocation Scheme

1. Dynamic Resource Allocation Outline

In general, each of the satellite and terrestrial components may have different traffic demands, depending on service requirements and the amount of interference relative to a user's location. In addition, as real traffic is non-uniform and time varying, the resource management system must reflect the different traffic distribution across all satellite beams and terrestrial cells. Some systems allocate only the transmission power based on the traffic demand. However, since the extreme demand of some users requires very high power compared with other beams or cells, this demand can cause more interference to others and reduce the total communication capacity. Therefore, power should be allocated according to both the time-variant traffic demand and the amount of inter-component interference within the networks.

The purpose of this resource allocation scheme is to maximize capacity while serving traffic demands by optimizing the total transmission power taking account of the considered interference environment. In other words, we can expect to mitigate the inter-component interference within the system by minimizing the power required to serve all beams and terrestrial cells with different traffic demands.

In this paper, there are two cases of inter-component interference to consider when implementing an integrated MSS system. In the first case, a group of terrestrial cells may interfere with a satellite beam that uses the co-channel of the terrestrial cells. In the second case, a satellite beam interferes with groups of terrestrial cells that belong to adjacent beams.

Taking into account the inter-component interference environments for an integrated MSS system with a reuse factor (N) of three, matrix C, which is composed of allocated power $E_b/N_0(i)$ for a beam, can be obtained as follows [8] (refer to Appendix):

$$G \cdot C_{9\times1} = \begin{bmatrix}1 & \cdots & 1\end{bmatrix}_{9\times1}^{T} \quad \text{for a reuse factor } (N) \text{ of three,} \tag{1}$$

where

$$C_{9\times1} = [C^1 \; C^2 \; C^3],$$

with

$$C^1 = [c_{11}c_{21}c_{31}]^T = \frac{1}{N_0}\left[E_{\mathrm{b}}{}^{S}(1), E_{\mathrm{b}}{}^{T_1}(1), E_{\mathrm{b}}{}^{T_2}(1)\right]^T,$$

$$C^2 = [c_{41}c_{51}c_{61}]^T = \frac{1}{N_0}\left[E_{\mathrm{b}}{}^{S}(2), E_{\mathrm{b}}{}^{T_1}(2), E_{\mathrm{b}}{}^{T_2}(2)\right]^T, \tag{2}$$

$$C^3 = [c_{71}c_{81}c_{91}]^T = \frac{1}{N_0}\left[E_{\mathrm{b}}{}^{S}(3), E_{\mathrm{b}}{}^{T_1}(3), E_{\mathrm{b}}{}^{T_2}(3)\right]^T.$$

Considering the integrated MSS system with a reuse factor (N) of three, in this paper we presented the generalized matrix G as expressed by (3).

$$G = \begin{bmatrix} \Delta_1 & 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & \Delta_2 & 0_{3\times3} \\ 0_{3\times3} & 0_{3\times3} & \Delta_3 \end{bmatrix}. \tag{3}$$

Here, matrix Δ_i of the diagonal elements in (3) is denoted in terms of the inter-component interference between the beam and cells using the co-channel, as given by

$$\Delta_i = \begin{bmatrix} \dfrac{1}{\rho^S(i)} & -\dfrac{R_{\mathrm{b}}{}^{T_1}(i)}{W_i}G_{T_1,S}(i) & -\dfrac{R_{\mathrm{b}}{}^{T_2}(i)}{W_i}G_{T_2,S}(i) \\ -\dfrac{R_{\mathrm{b}}{}^{S}(i)}{W_i}G_{S,T_1}(i) & \dfrac{1}{\rho^{T_1}(i)} & 0 \\ -\dfrac{R_{\mathrm{b}}{}^{S}(i)}{W_i}G_{S,T_2}(i) & 0 & \dfrac{1}{\rho^{T_2}(i)} \end{bmatrix}, \tag{4}$$

where $R_{\mathrm{b}}(i)$ is the required bit rate of each beam and group of terrestrial cells and W_i is the ith frequency band of the beam (or cells). As $G_{i,j}(=g_{i,j}/g_{i,i})$ is the relevant term for the antenna gain, here $g_{i,j}$ is the antenna gain from beam (or cell) j to beam (or cell) i. In addition, $\rho(i)$ is averaged as $E_{\mathrm{b}}/(N_0+I_0)$, where I_0 is the interference power density, assuming it is determined properly by applying the appropriate AMC according to the spectral efficiency that can achieve the Shannon capacity; $\rho(i)$ is then calculated by

$$2^{R_{\mathrm{b}}(i)/W_i} - 1 \tag{5}$$

from the ith capacity C_i=$W_i\log_2(1+\rho(i))$, while fully serving the traffic demand, $R_{\mathrm{b}}(i)$ [9]. Table 1 classifies the satellite beam and terrestrial cell groups using frequency f_i. For the S, T_1, and T_2 noted in the Table 1, S indicates a satellite beam and T_1 and T_2 are the groups of terrestrial cells using the same frequency in the inter-beams, as given in Table 2. In this paper, we propose an adaptive bandwidth allocation scheme according to the traffic demands and interference between inter-components, which can achieve a minimization of the required transmission power among the beams and terrestrial cells. Based on this assumption and environment, we derive the dynamic resource allocation algorithm in the next section.

Table 1. Information relating to satellite beam and terrestrial cell groups using f_i.

Required E_{b}/N_0	Required data rate	Averaged $E_{\mathrm{b}}/(N_0+I_0)$	Antenna gain
$\frac{E_{\mathrm{b}}^S}{N_0}(i)$	$R_{\mathrm{b}}{}^S(i)$	$\rho^S(i)$	$G_{S,T_1}(i)$, $G_{S,T_2}(i)$
$\frac{E_{\mathrm{b}}^S}{N_0}(i)$	$R_{\mathrm{b}}{}^{T_1}(i)$	$\rho^{T_1}(i)$	$G_{T_1,S}(i)$
$\frac{E_{\mathrm{b}}^S}{N_0}(i)$	$R_{\mathrm{b}}{}^{T_2}(i)$	$\rho^{T_2}(i)$	$G_{T_2,S}(i)$

Table 2. Definition of notation used in Table 1.

i	$S(i)$	$T_1(i)$	$T_2(i)$
1	ith satellite beam using f_i	Terrestrial cell group in (i+1)th satellite beam	Terrestrial cell group in (i+2)th satellite beam
2		Terrestrial cell group in (i–1)th satellite beam	Terrestrial cell group in (i+1)th satellite beam
3		Terrestrial cell group in (i–2)th satellite beam	Terrestrial cell group in (i–1)th satellite beam

2. Modeling of Optimum Resource Allocation

To derive this adaptive resource allocation model, we find an optimized design by minimizing the general function of the total consumed transmission power, thereby minimizing the inter-component interference. If we use a cost function in terms of the total consumed power $E_{\mathrm{b}}/N_0(i)$, the problem can be modeled as

$$\underset{W_i}{\arg\min} \sum_{i=1}^{N} \left\{ \frac{E_{\mathrm{b}}^S}{N_0}(i) + \frac{E_{\mathrm{b}}^{T_1}}{N_0}(i) + \frac{E_{\mathrm{b}}^{T_2}}{N_0}(i) \right\} \text{ for } i = 1, 2, \ldots, N. \tag{6}$$

To derive each $E_{\mathrm{b}}/N_0(i)$, inserting (4) into (1) results in

$$\frac{E_{\mathrm{b}}^S}{N_0}(i) = \frac{\rho^S(i) + \Gamma_{S,T_1} + \Gamma_{S,T_2}}{1 - \Pi_1 - \Pi_2}, \tag{7}$$

where

$$\Gamma_{S,T_1} = \frac{R_{\mathrm{b}}^{T_1}(i)}{W_i}\rho^{S}(i)\rho^{T_1}(i)G_{T_1,S}(i), \tag{8}$$

$$\Gamma_{S,T_2} = \frac{R_{\mathrm{b}}^{T_2}(i)}{W_i}\rho^{S}(i)\rho^{T_2}(i)G_{T_2,S}(i), \tag{9}$$

$$\Pi_1 = \left\{\frac{R_{\mathrm{b}}^{S}(i)}{W_i}G_{S,T_1}(i)\right\}\cdot\Gamma_{S,T_1}, \quad \text{and} \quad \Pi_2 = \left\{\frac{R_{\mathrm{b}}^{S}(i)}{W_i}G_{S,T_2}(i)\right\}\cdot\Gamma_{S,T_2}. \tag{10}$$

In addition, the $E_{\mathrm{b}}/N_0(i)$ related to the terrestrial components is as follows:

$$\frac{E_{\mathrm{b}}^{T_1}}{N_0}(i) = \rho^{T_1}(i)\left\{1+\frac{R_{\mathrm{b}}^{S}(i)}{W_i}G_{S,T_1}(i)\frac{E_{\mathrm{b}}^{S}}{N_0}(i)\right\}, \tag{11}$$

$$\frac{E_{\mathrm{b}}^{T_2}}{N_0}(i) = \rho^{T_2}(i)\left\{1+\frac{R_{\mathrm{b}}^{S}(i)}{W_i}G_{S,T_2}(i)\frac{E_{\mathrm{b}}^{S}}{N_0}(i)\right\}. \tag{12}$$

Since there are so many parameters to be considered, it is essential to come up with the appropriate constraints to find the global optimum solution. Here, we consider the constraint condition to simplify the problem while minimizing interference, as motivated by [8]. The bandwidth constraints must be properly set to minimize interference. Figure 3 illustrates the interference considerations. For the first condition, three frequency bands fully use the entire system bandwidth W_{tot} to maximize spectral efficiency. The overlapped frequency band in regard to the same frequency area causes interference. Consequently, the second condition is to prevent extreme interference by applying each beam and terrestrial cell in the same frequency, f_i, which should have the same amount of frequency bandwidth.

By considering these constraints, secure low-interference situations can be expected, as the complexity of the formulated optimization problem can be reduced. In this regard, the constraints with respect to the frequency bandwidth to be allocated can be formulated as below.

$$\sum_{i=1}^{N} W_i \le W_{tot} \quad \text{for } i = 1, 2, \ldots, N, \tag{13}$$

$$W_i \ge 0, \tag{14}$$

where the first constraint in (13) indicates that the whole bandwidth assignment does not exceed the total system bandwidth. The condition in (14) is added to see which beam or cell should be served with non-zero bandwidth. The Lagrangian function is applied as

$$L(W_i,\lambda_i) = \left\{\frac{E_b}{N_0}\right\}_{\text{sum}} + \lambda_1\Big(\sum_{i=1}^{N} W_i - W_{tot}\Big) - \lambda_2\Big(\sum_{i=1}^{N} W_i\Big), \tag{15}$$

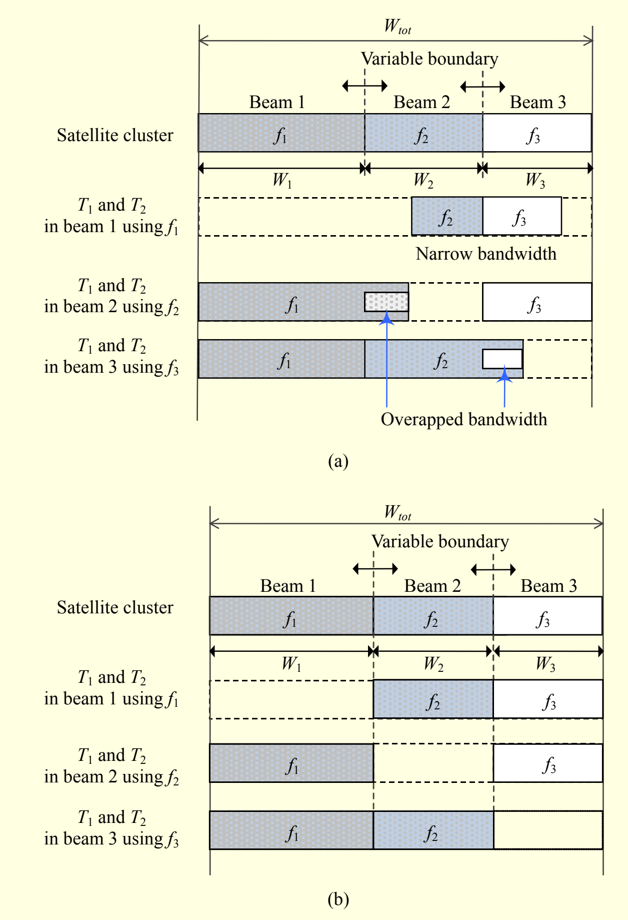

Fig. 3. Bandwidth constraints for minimizing inter-component interference between the satellite beam and terrestrial cells.

where λ_1 and λ_2 are the Lagrangian multipliers and the Karush–Kuhn–Tucker (KKT) condition [10] can yield $\lambda_1, \lambda_2 \ge 0$ and $\lambda_2 W_i = 0$. Intuitively, this implies that λ_2 should become zero to allocate the non-zero bandwidth. Using the KKT condition results in

$$\frac{\partial L(W_i,\lambda_i)}{\partial \lambda_i} = 0. \tag{16}$$

By applying condition (16) to (15) again, we can derive the optimum beam profile in terms of W_i as

$$\lambda_1 W_i^4 - (2C\lambda_1 + G)W_i^2 - (AC + 2DE + 2EF)W_i + \lambda_1 C^2 - CG = 0, \tag{17}$$

where

$$A = 2\rho_1^i, \tag{18}$$

$$B = R_{\mathrm{b}2}^i \rho_1^i \rho_2^i g_{21}^i + R_{\mathrm{b}3}^i \rho_1^i \rho_3^i g_{31}^i, \tag{19}$$

$$C = R_{\mathrm{b}1}^i R_{\mathrm{b}2}^i \rho_1^i \rho_2^i g_{12}^i g_{21}^i + R_{\mathrm{b}1}^i R_{\mathrm{b}3}^i \rho_1^i \rho_3^i g_{13}^i g_{31}^i, \tag{20}$$

$$D = R_{\mathrm{b}1}^i \rho_1^i \rho_2^i g_{12}^i, \tag{21}$$

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$$E = R_{\mathrm{b}1}^{i}\rho_1^{i}\rho_3^{i}g_{13}^{i}\,, \tag{22}$$

$$F = R_{\mathrm{b}2}^{i}\rho_2^{i}g_{21}^{i} + R_{\mathrm{b}3}^{i}\rho_3^{i}g_{31}^{i}\,, \tag{23}$$

and
$$G = B + D + F. \tag{24}$$

In general, there are many methods to solve a biquadratic polynomial, such as (17), and we can speculate whether its roots have real or imaginary values from its discriminant [11]. A meaningful intuition can be drawn from closed-form solutions by selecting the smallest real number among the values of equation (17), and we confirmed that it makes sense using an exhaustive search. In the next section, the required transmission power of each beam and group of terrestrial cells using the optimum bandwidth to be allocated by the proposed resource allocation scheme is demonstrated, and the performance of uniform bandwidth allocation, regardless of the traffic demand and interference over all beams and cells, is compared.

IV. Analytical Simulation Results

For the simulation, we create a simplified model as follows. In a network, there is a multi-beam satellite with groups of terrestrial cells that reuse the same frequency band, and the total system bandwidth is 10 MHz. In addition, we assume the traffic demands of each beam and cell are generated randomly, as shown in Table 3 (total traffic demand is 45 Mbit/s).

Figure 4 shows the transmission powers required to serve the generated data rates, based on the amount of inter-component interference. Here, the amount of interference between the satellite beam and terrestrial components using the same frequency are assumed as follows. For simplicity, we assume that there are three cases of inter-component interference. For the first case, it can be considered that the satellite beam may interfere with the groups of terrestrial cells using the same frequency band and that the signal strength is 5%. In addition, we assume that interference of the satellite beam affected from the first group of terrestrial cells that exists in the adjacent beam is set to the terrestrial component strength of 10%, which is about $T_1(i)$, as defined in Table 2. The received amount of interference to the satellite beam $S(i)$ from another group of terrestrial components $T_2(i)$ is also assumed to be somewhat heavy; that is, 30% of the strength of $T_2(i)$. The *i*th frequency bandwidths that are allocated by the uniform allocation and proposed dynamic resource allocation schemes, according to the data rates set in Table 3, are shown in Table 4. Inserting W_i into equations (7), (11), and (12) results in the required power of each satellite beam and group of terrestrial cells, as shown in Fig. 4. The purpose of the proposed resource allocation is to minimize the total consumed power that can reduce the inter-component interference, while satisfying the required data rates. In this regard, we can confirm that the proposed scheme coincides more closely to our objective of this resource allocation through a comparison of the total sum of the consumed power shown in Table 5.

Figure 5 also shows the inter-component interference within the system after applying the two resource allocation schemes. We can see that the performance of the interference mitigation of the proposed algorithm is superior to that of a uniform resource allocation scheme. Under this situation, we can expect

Table 3. Required traffic demand for each satellite beam and group of terrestrial cells (Mbit/s).

Beam or cells *i*th W_i	$S(i)$	$T_1(i)$	$T_2(i)$
1	6	3	7
2	5	4	3
3	5	9	3

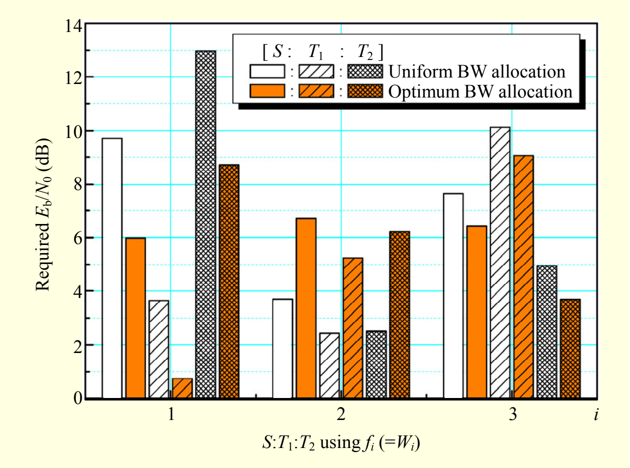

Fig. 4. Comparison of consumed power based on the data rate and inter-component interference.

Table 4. Optimum frequency bands based on the resource allocation schemes.

*i*th W_i Resource allocation	1	2	3
Uniform	3.33 MHz	3.33 MHz	3.33 MHz
Optimum	3.8 MHz	2.7 MHz	3.5 MHz

Table 5. Sum of the consumed power based on the simulation results of Fig. 4.

Resource allocation	Uniform	Optimum
Total consumption of power	17.5274 dB	15.9779 dB

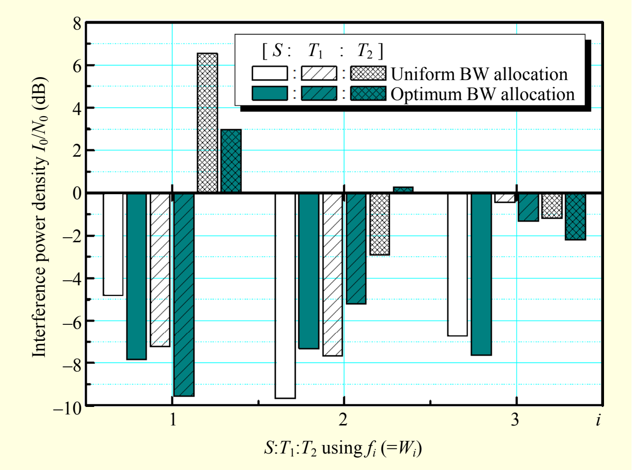

Fig. 5. Comparison of inter-component interference using uniform bandwidth allocation and the proposed optimization scheme.

Table 6. Total inter-component interference based on the simulation results of Fig. 5.

Resource allocation	Uniform	Optimum
Total inter-component interference	8.8584 dB	7.2605 dB

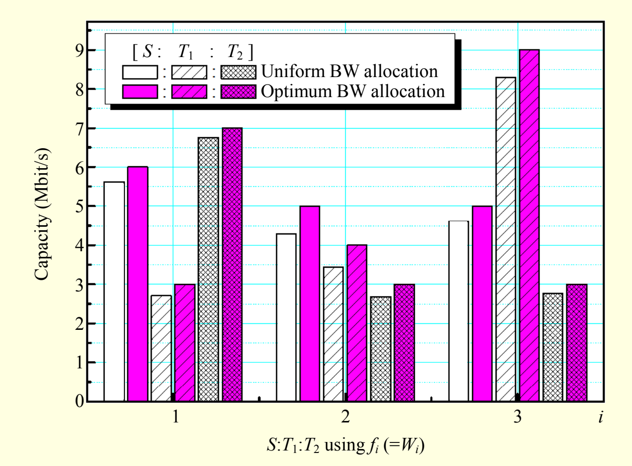

Fig. 6. Performance comparison of achievable capacities under the total power constraint.

Table 7. Comparison of total capacity under the total transmission power constraint

Resource allocation	Uniform	Optimum
Total capacity	41.185 (Mbit/s)	45 (Mbit/s)

a mitigation gain of interference of about 1.6 dB compared to a uniform allocation scheme, as shown in Table 6. From the results in Table 5, we found that the proposed scheme can save transmission power and satisfy the required traffic demand to each beam and terrestrial cell.

Figure 6 and Table 7 show the capacity performance of the proposed scheme assuming that it is only permitted the total consumed power necessary to support the generated traffic demands shown in Table 3; in other words, the total consumed power is limited to 15.9779 dB. Indeed, we can see an improved performance in the total capacity as compared to a conventional uniform allocation of about 3.8 Mbit/s.

As a result, the proposed interference-limited dynamic resource allocation can be performed by minimizing the total power consumption of an integrated satellite and terrestrial system. It is noted in the proposed scheme that the less transmit power produced, the less inter-component interference; thus, we can achieve higher capacity with less transmit power compared to the uniform power allocation. In addition, it is shown in the case of the uniform power allocation scheme that the traffic demands for both satellite and terrestrial components cannot be satisfied for the power-limited environment considering that satellite resources are expensive and scarce; thus, quality of service might not be guaranteed. On the other hand, from the point of view of complexity, the proposed scheme is surely more complex than the uniform allocation scheme, but its computational complexity has a linearly increasing function in the number of beams by applying the approach in Fig. 3(b), compared to many other dynamic resource allocation schemes whose complexity are under an exponentially increasing function. Therefore, in practical satellite/terrestrial systems, we believe that the proposed scheme has the advantage that traffic demands for both components can be supported on time with minimized power consumption and that it will have reasonable computational complexity.

V. Conclusion

New satellite operators adopting MSSs using a terrestrial component approach have been actively developing frequency reuse schemes that optimize spectral efficiency and increase system capacity. In this paper, we proposed a dynamic resource allocation scheme based on the traffic demand and inter-component interference for an integrated multi-beam satellite and terrestrial system. The proposed scheme aims to increase system capacity by optimizing the required amount of consumed power, which means a minimization of interference within the system. Based on the simulation results, the proposed resource allocation scheme can achieve a better performance by saving the total consumed power to serve the required data rates, compared to a uniform allocation scheme. In addition, the capacity gain from the proposed scheme is superior to that from a uniform allocation scheme. This means we can eventually expect to construct a cost-effective and flexible network for integrated systems.

Appendix. General Matrix for Frequency Reuse *N*

To apply the integrated MSS system with reuse factor *N*, we derive the generalized matrix *G* from the matrix related to the required power for the multi-beam satellite network introduced in [8], as given by (25).

$$G \cdot \frac{1}{N_0} \begin{bmatrix} E_{\mathrm{b}}^{S}(1) \\ E_{\mathrm{b}}^{T_1}(1) \\ E_{\mathrm{b}}^{T_2}(1) \\ \vdots \\ E_{\mathrm{b}}^{T_{N-1}}(1) \\ E_{\mathrm{b}}^{S}(2) \\ E_{\mathrm{b}}^{T_1}(2) \\ E_{\mathrm{b}}^{T_2}(2) \\ \vdots \\ E_{\mathrm{b}}^{T_{N-1}}(2) \\ \vdots \\ \vdots \\ E_{\mathrm{b}}^{S}(N) \\ E_{\mathrm{b}}^{T_1}(N) \\ \vdots \\ E_{\mathrm{b}}^{T_{N-1}}(N) \end{bmatrix}_{N^2 \times 1} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{N^2 \times 1} \quad \text{for } i = 1, 2, \ldots, N. \qquad (25)$$

The descriptions of the symbols are omitted here because they were given previously. As matrix *G* is related with the signal-to-interference-plus-noise ratio $E_{\mathrm{b}}/(I_0+N_0)$, its diagonal elements are tied up with respect to the satellite beam and terrestrial component using the same frequency. This means that the non-diagonal elements of *G* become zeroes since the satellite beam and terrestrial cells using a different frequency band are not associated; that is, there is no interference.

$$G = \begin{bmatrix} \Delta_1 & 0_{N\times N} & 0_{N\times N} & 0_{N\times N} \\ 0_{N\times N} & \Delta_2 & 0_{N\times N} & 0_{N\times N} \\ 0_{N\times N} & 0_{N\times N} & \ddots & 0_{N\times N} \\ 0_{N\times N} & 0_{N\times N} & 0_{N\times N} & \Delta_{N^2} \end{bmatrix}_{N^2\times N^2}. \qquad (26)$$

Considering the inter-component interference between a satellite beam and group of terrestrial cells, Δ_i results in

$$\Delta_i = \begin{bmatrix} \frac{1}{\rho^S(i)} & -\frac{R_{\mathrm{b}}^{T_1}(i)}{W_i} G_{T_1,S}(i) & \cdots & -\frac{R_{\mathrm{b}}^{T_{N-1}}(i)}{W_i} G_{T_{N-1},S}(i) \\ -\frac{R_{\mathrm{b}}^{S}(i)}{W_i} G_{S,T_1}(i) & \frac{1}{\rho^{T_1}(i)} & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ -\frac{R_{\mathrm{b}}^{S}(i)}{W_i} G_{S,T_{N-1}}(i) & 0 & 0 & \frac{1}{\rho^{T_{N-1}}(i)} \end{bmatrix}. \qquad (27)$$

Here, the first row of Δ_i shows the pertinent terms used to find the required power of a satellite beam using the *i*th frequency band, and the other terms except the first column element related to $\rho^S(i)$ indicate the interference for the satellite beam from the groups of terrestrial cells that use the same frequency band in contiguous beams. Now, to derive a simpler mathematical formulation, we can obtain (3) by applying an integrated MSS system, particularly considering a reuse factor (*N*) of three.

References

[1] U. Park et al., “A Dynamic Bandwidth Allocation Scheme for a Multi-spot-beam Satellite System,” *ETRI J.*, vol. 34, no. 4, Aug. 2012, pp. 613–616.

[2] S.Y. Kim et al., “Evaluation of Cooperative Diversity Techniques Using STC for Future S-DMB Services,” *IEICE Trans. Commun.*, vol. E92-B, no. 11, Nov. 2009, pp. 3345–3353.

[3] ITU-R, Doc. IMT-ADV-SAT/4, *Acknowledgement of Candidate Submission from Republic of Korea under Step 3 of the Satellite IMT-Advanced Process (SAT-OFDM)*, May 2012.

[4] B. Evans et al., “Integration of Satellite and Terrestrial Systems in Future Multimedia Communications,” *IEEE Wireless. Commun.*, vol .12, no. 5, Oct. 2005, pp. 72–80.

[5] V. Deslandes, J. Tronc, and A.-L. Beylot, “Analysis of Interference Issues in Integrated Satellite and Terrestrial Mobile Systems,” *Adv. Satellite Multimedia Syst. Conf. (ASMA) Signal Process. Space Commun. Workshop (SPEC),* Cagliari, Italy, Sept. 13–15, 2010, pp. 256–261.

[6] P.D. Karabinis, S. Dutta, and W. Chapman, “Interference Potential to MSS DUE to Terrestrial Reuse of Satellite Band Frequencies,” *Int. Commun. Satellite Syst. Conf.*, Rome, Italy, Sept. 2005.

[7] M. Sadek and S. Aissa, “Personal Satellite Communication: Technologies and Challenges,” *IEEE Wireless Commun.*, vol. 19, no. 6, Dec. 2012, pp. 28–35.

[8] K. Nakahira, K. Kobayashi, and M. Ueba, “Capacity and Quality Enhancement Using an Adaptive Resource Allocation for Multi-beam Mobile Satellite Communication Systems,” *Wireless Commun. Netw. Conf.*, Las Vegas, NV, USA, vol. 1, Apr. 2006, pp. 153–158.

[9] T.M. Cover and J.A. Thomas, *Elements of Information Theory*, New York: John Wiley & Sons, Inc., 1991.

[10] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge University Press, 2004.

[11] D.P. Bertsekas, *Nonlinear Programming*, Belmont, MA: Athena Scientific, 1995.

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