A Dynamic Bandwidth Allocation Scheme for a Multi-spot-beam Satellite System

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

A multi-spot-beam satellite is an attractive technique for future satellite communications since it can support high data rates by projecting high power density to each spot beam and can reuse a frequency in different cells to increase the total system capacity. In this letter, we propose a resource management technique adjusting the bandwidth of each beam to minimize the difference between the traffic demand and allocated capacity. This represents a reasonable solution for dynamic bandwidth allocation, considering a trade-off between the maximum total capacity and fairness among the spot beams with different traffic demands.

Keywords: Multibeam satellite, resource allocation, frequency bandwidth, spectral efficiency, optimization.

I. Introduction

The world's resources are limited but traffic demands are increasing rapidly. In this environment, it is important to prevent the waste of resources while maximizing the effectiveness of their utilization and improving the total system capacity [1]. As part of this effort, the allocated capacity of each beam should be changed adaptively according to the time-variant traffic distribution over multibeam satellite downlinks.

A satellite with multi-spot-beams will play an important role in future satellite communication systems since it is possible not only to provide high data rates to small user terminals but also to construct flexible service networks. In this multibeam satellite system, since satellite resources such as power, bandwidth, and the use of a spot beam are expensive and scarce, the effort to enhance their efficiency is crucial.

In general, each spot beam may have different traffic demands as well as channel conditions depending on the service requirements and locations of the users. In addition, as real traffic is non-uniform and time varying, the resource management must reflect the different traffic distribution and channel conditions across all spot beams.

In previous research [2], [3], dynamic power allocation schemes have been proposed using the advantages of multiple beams, in which capacity gain is monotonically increased with the number of beams. However, these conventional schemes require an on-board power amplifier to operate with high input back-off, inducing performance degradation due to the different power allocations for each beam. To solve this problem, we consider adjusting the amount of bandwidth to be allocated into the spot beam to maximize the spectral efficiency. In this letter, we propose an adaptive bandwidth allocation scheme according to traffic demands and weather-induced signal attenuation, which can achieve a reasonable solution between the maximization of total capacity and the support of proportional fairness among the beams.

II. Proposed Dynamic Bandwidth Allocation Scheme

1. Backgrounds and Motivations

Figure 1 shows the system configuration of a multi-spot-beam satellite. In the network, a multi-spot-beam satellite in geostationary orbit and an ensemble of spot beam cells are deployed. Each beam requires demand T_i and signal attenuation α_i^2 (≤ 1) caused by the weather conditions. Using time sharing for Gaussian broadcast channels [4], we can obtain the Shannon bounded capacity C_i for the i-th beam as

$$C_i = W_i \log_2(1+\rho_i), \quad (1)$$

where $\rho_i = \alpha_i^2 P/(W_i N_0)$ and P and N_0 indicate the allocated

---

Manuscript received Oct. 18, 2011; revised Feb 24, 2012; accepted Mar. 7, 2012.

Unhee Park (phone: +82 42 860 1306, unipark@etri.re.kr), Hee Wook Kim (prince304@etri.re.kr), Dae Sub Oh (trap@etri.re.kr), and Bon-Jun Ku (bjkoo@etri.re.kr) are with the Broadcasting & Telecommunications Convergence Research Laboratory, ETRI, Daejeon, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.12.0211.0437

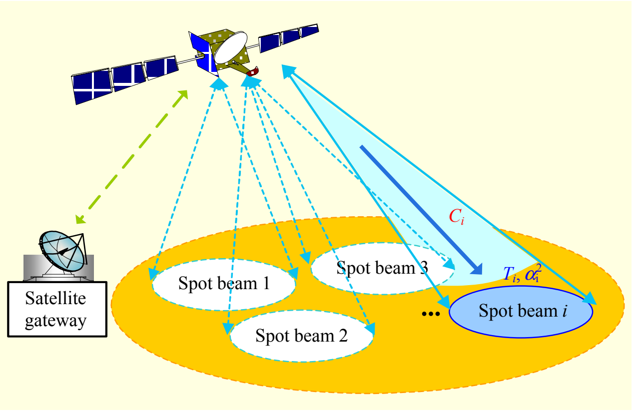

Fig. 1. System configuration of multi-spot-beam satellite.

power and noise power density, respectively. In addition, W_i is the allocated bandwidth that can be adjusted to optimize resource use. In this letter, we mainly consider that downlink channels have the property of rainfall attenuation, which is a slow fading event, as well as uniform attenuation across each spot beam. In addition, we assume that inter-beam interference that can be induced from adjacent beams is negligible, by considering very narrow beams over a large number of cells [5].

If the total system bandwidth is sufficient to support an aggregate traffic demand generated by the overall spot beams, the adaptive allocation scheme may be meaningless. However, as noted above, the study on effective resource management deserves sufficient consideration in a communications environment with a scarcity of resources. Therefore, we only focus on the resource allocation in which the total traffic demand exceeds the whole available system capacity across all of the spot beams. In this regard, we introduce a dynamic bandwidth allocation scheme to provide a reasonable solution considering a trade-off between the total system capacity and fairness among the spot beams with different traffic demands.

2. Dynamic Bandwidth Allocation

Minimization of the difference between the supported capacity C_i and traffic demand T_i in the i-th beam can provide a reasonable objective for resource allocation, considering a trade-off between the maximization of the total system capacity and proportional fairness among spot beams in which traffic demands are generated. In II.1., we assumed that the total system capacity cannot meet the total traffic demand. Thus, we adopt a square deviation cost function between the capacity and traffic demand for each beam and formulate the modeling of a dynamic bandwidth allocation problem as

$$\arg\min_{C_i} \sum_{i=1}^{n} (T_i - C_i)^2, \tag{2}$$

where $\quad C_i = W_i \log_2(1+\rho_i) \le T_i \quad \text{for } i=1, 2, \ldots, n, \qquad (3)$

$$\sum_{i=1}^{n} W_i \le W_{\text{total}}, \tag{4}$$

where n is the number of spot beams. The first constraint in (3) indicates that the i-th allocated bandwidth is never more than the demand required from the beam to prevent an unnecessary waste of resources.

The condition of (4) implies that the whole bandwidth assignment does not exceed the total system bandwidth. Applying the Lagrangian function as $L(W_i,\Lambda)=\sum_i (T_i-C_i)^2 +\Lambda(\sum_i W_i - W_{\text{total}})$, we can derive the optimum beam profile in terms of W_i as

$$T_i - W_i \log_2(1+\rho_i) = \frac{\frac{\Lambda \ln 2}{2}(1+\rho_i)}{\ln 2(1+\rho_i)\log_2(1+\rho_i) - \rho_i}, \tag{5}$$

where Λ is a Lagrange multiplier that is determined by the total bandwidth constraint of (4). If Λ is a nonnegative value, it means that the bandwidth determined by (5) satisfies the constraint $C_i \le T_i$ of (3). In general, the proposed beam profile (5) does not have a closed-form solution with respect to W_i, and, thus, it can be solved numerically to obtain the optimum bandwidth W_i in terms of traffic demand T_i. As we mentioned, the dynamic power allocation scheme of [3] was introduced using the advantages of parallel multiple beams. However, it only handled an approximated solution in the case of signal-to-noise ratio (SNR)<<1 and SNR>>1, and there was no method to approach the numerical solution definitely. Therefore, we present a proper way to find the numerical solution for W_i in subsection II.3.

3. Solution to Obtain i-th Optimum Bandwidth

To find the optimum bandwidth of the i-th beam, we apply an intuitive and meaningful approach to decode the relationship between traffic demands and the proposed beam profile in terms of W_i. In this method, the Lagrange multiplier Λ is determined according to the total bandwidth constraint. From (5), it can be derived, as given by (6):

$$\Lambda = \frac{2}{\ln 2}(T_i - C_i) \times \frac{\ln 2(1+\rho_i)\log(1+\rho_i) - \rho_i}{1+\rho_i}. \tag{6}$$

First, to obtain the initial value Λ_0 for Λ, we assume that the total bandwidth is allocated to a spot beam in which the traffic demand corresponding to the sum of the traffic demands across all the beams ($\sum_i T_i = T_{\text{sum}}$) occurs. Therefore, T_{sum} and W_{total} are put into T_i and W_i of (6), respectively, to obtain the initial value, Λ_0. Next, using the binary search approach as a foundational rule, we set a range of $\Lambda_{\min}=\Lambda_0/k$ and $\Lambda_{\max}=\Lambda_0\times k$ in which the

Table 1. Update process of Lagrange multiplier Λ ($\overline{\Lambda}$: previous state).

Condition \ Symbol	$\Lambda_{\min}$	$\Lambda_{\max}$	Λ
$\Sigma W_i^{\mathrm{iter}} > W_{\mathrm{total}}$	Λ	$\overline{\Lambda}_{\max}$	$(\Lambda_{\min}+\Lambda_{\max})/2$
$\Sigma W_i^{\mathrm{iter}} < W_{\mathrm{total}}$	$\overline{\Lambda}_{\min}$	Λ	$(\Lambda_{\min}+\Lambda_{\max})/2$

final optimum value Λ^{opt} can be placed. The value of k is a constant of larger than 2. After determining the initial values of $\Lambda_{\min}$ and $\Lambda_{\max}$ from Λ_0, the procedure used to update these values as well as to find the optimum bandwidth for each beam is as follows.

Step 1. Find the initial values of W_i, called W_i^{iter}, and the sum of those using the optimum beam profile of (5) and Λ_0.

Step 2. Updating Λ, $\Lambda_{\min}$, and $\Lambda_{\max}$ according to the conditions specified in Table 1, recalculate W_i^{iter} and $\sum_i W_i^{\mathrm{iter}}$ using the updated Lagrange multiplier Λ instead of Λ_0.

Step 3. Carry out the process of Step 2 iteratively until $\sum_i W_i^{\mathrm{iter}} = W_{\mathrm{total}}$.

According to the above process, we finally obtain the optimum bandwidth for each beam when the Lagrangian multiplier Λ reaches its final value Λ^{opt}.

4. Approximated Closed-Form Solutions

Motivated by [3], we can analyze an aspect of the numerical solution using an approximated closed-form solution according to low and high SNRs. At a low SNR region with $\rho_i \ll 1$, applying the property of $\log_2(1+x) \approx x/\ln 2$ for a very small x, we can derive the first-order approximation formula from (5):

$$W_i = \begin{cases} \dfrac{2\alpha_i^2 P}{\Lambda N_0 \ln 2}\left(T_i - \dfrac{\alpha_i^2 P}{N_0 \ln 2}\right), & \text{if } T_i > \dfrac{\alpha_i^2 P}{N_0 \ln 2}, \\ 0, & \text{if } T_i \le \dfrac{\alpha_i^2 P}{N_0 \ln 2}. \end{cases} \tag{7}$$

Looking at the expression of (7), we can speculate that the amount of increase in the allocated bandwidth is small compared to the increase in traffic demand resulting from the fact that it has a relatively small slope about T_i.

Next, we use a truncated part of the Taylor series of $\log_2(1+x) \approx (x/\ln 2) - (x^2/2\ln 2)$ for the high SNR region with $\rho_i \gg 1$, and we also obtain the third-order approximation:

$$\beta_1 W_i^3 + \beta_2 W_i^2 + \beta_3 W_i + \beta_4 = 0, \tag{8}$$

where $\beta_1 = \dfrac{\Lambda(\ln 2)^2}{(\alpha_i^2 P)^3}$, $\beta_2 = \dfrac{2}{\alpha_i^2 P N_0^{\,2}} - \dfrac{T_i \ln 2}{(\alpha_i^2 P)^2 N_0}$,

$$\beta_3 = \frac{T_i \ln 2}{\alpha_i^2 P N_0^{\,2}} - \frac{2}{N_0^{\,3}}, \quad \beta_4 = \frac{\alpha_i^2 P}{2 N_0^{\,4}}. \tag{9}$$

In general, there are many methods to solve the cubic polynomial, such as (8), and we can speculate whether its roots have real or imaginary values from its discriminant [6]. With the discriminant of (8), we can finally determine that only one root has a real number and the others have imaginary numbers. Inferring from (8) and (9), we can find that W_i and T_i are inversely related.

III. Analytical Simulation Results

For the simulation, we create a simplified model as follows. A multibeam geostationary satellite at the S-band is considered, and on-board transmission power is uniformly distributed by the number of spot beams. In this letter, we mainly consider the problem of resource allocation in the physical layer on the assumption that the transport layer will serve in the case of excess demands so as to suppress the delay issue. In other words, we only focus on the long-term average gain with respect to the Shannon capacity and spectral efficiency. As noted earlier, we assume the uniform signal attenuation ($\alpha_i^2=1$) across each spot beam and set the k factor to 10 to determine the range for searching the final optimal Λ.

Figure 2 represents the SNR of each beam ($=P/(W_i N_0)$) decided by the beam bandwidth (W_i) allocated according to the traffic demand on each beam. The values are obtained from the numerical solution of (5) as well as the approximated solutions of (7) and (8). By focusing on the low SNR region, it is shown in the figure that each beam bandwidth in the numerical solution is allocated in a similar way to the first-order approximation. On the other hand, for the high SNR region, the beam bandwidth allocation is achieved along with that of the third-order approximation. This means that the approximated

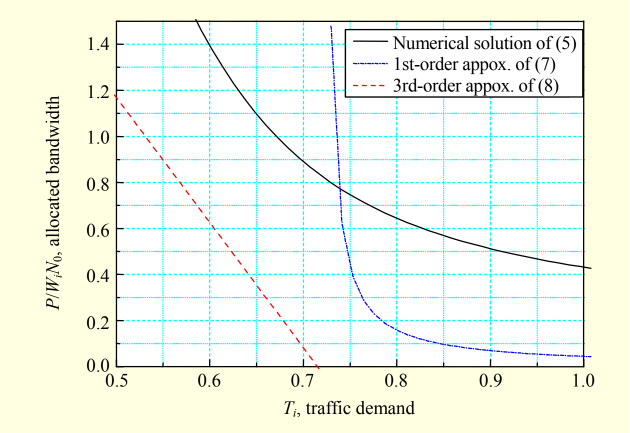

Fig. 2. Optimum distribution of bandwidth W_i for demand T_i in (5).

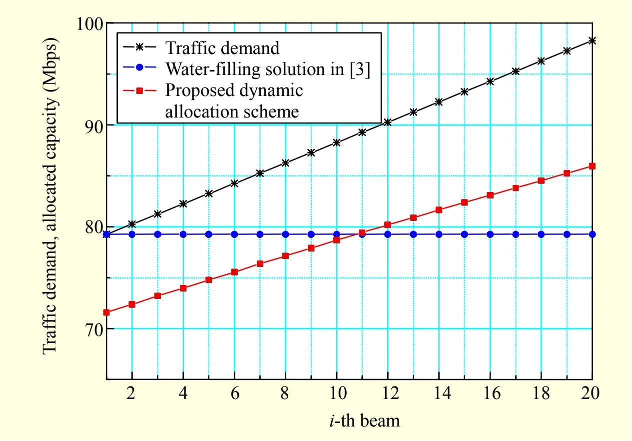

Fig. 3. Distribution of capacities for two resource allocations along spot beams having linearly increased distribution of traffic demand.

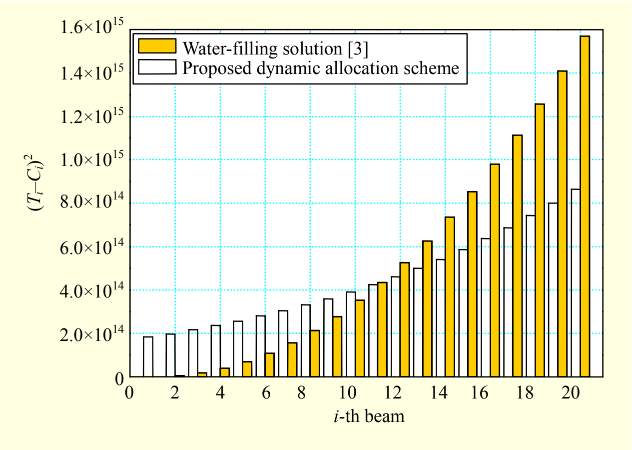

Fig. 4. Distribution of gap between traffic demand and capacity, $(T_i-C_i)^2$ based on simulation result of Fig. 3.

closed-form solutions based on meaningful intuition are sensibly derived and show the validity of the proposed optimum beam profile in terms of W_i.

We assume in Figs. 3 and 4 that the total system bandwidth is 1 GHz, on-board EIRP is 80.329 dBW, and the propagation loss with free-space in 2.5 Hz is 191.53 dB [7]. Figure 3 shows the capacity distributions of spot beams that are allocated by uniform and dynamic bandwidth allocation schemes. It is well known that the maximum total capacity can be achieved by a water-filling approach and a uniform resource allocation would be the water-filling solution when the traffic demand on each beam exceeds the capacity allocated in the beam [3]. It means that the uniform bandwidth allocation scheme in Fig. 3 can be regarded as a dynamic bandwidth allocation scheme for total capacity maximization because the allocated capacity for each beam is smaller than the traffic demand on each beam in the figure. As shown in Fig. 3, a uniform bandwidth allocation scheme can achieve greater total system capacity than can the proposed dynamic allocation scheme (the total capacity of uniform and dynamic allocations are 1,585.0 Mbps and 1,578.7 Mbps, respectively). However, in this letter, we handle the trade-off problem between total capacity and fairness among the spot beams, which is aimed at providing a reasonable solution for proportional fairness. From the results shown in Fig. 3, the proposed dynamic allocation scheme can achieve more proportional fairness across all spot beams but at a cost in total capacity. In this regard, we focus on the minimization of the gap between supported C_i and T_i, and this difference of each beam is shown in Fig. 4. In addition, we can confirm that the proposed scheme coincides more closely to the objective of this resource allocation through a comparison of the total sums of the gaps, $\sum(T_i-C_i)^2$, being 2.4754E15 for the water-filling method and 1.9696E15 for the proposed scheme.

IV. Conclusion

In this letter, we proposed a dynamic bandwidth allocation scheme based on the traffic distributions and channel conditions for a parallel multibeam satellite system. We studied the trade-off problem between maximum total capacity and proportional fairness among beams with traffic demand, considering the best case when available capacity matches demand under the assumption of a simplified model. The proposed bandwidth allocation scheme sacrifices total capacity but can nevertheless achieve more proportional fairness for all spot beams with different traffic demands.

References

[1] J. Ha, J. Kim, and S.-H. Kim, "Performance Analysis of Dynamic Spectrum Allocation in Heterogeneous Wireless Networks," *ETRI J.*, vol. 32, no. 2, Apr. 2010, pp. 292-301.

[2] M.J. Neely, E. Modiano, and C.E. Rohrs, "Power Allocation and Routing in Multibeam Satellites with Time-Varying Channels," *IEEE/ACM Trans. Netw.*, vol. 11, no. 1, Feb. 2003, pp. 138-152.

[3] J.P. Choi and V.W.S. Chan, "Optimum Power and Beam Allocation Based on Traffic Demand and Channel Conditions over Satellite Downlinks," *IEEE Trans. Commun.*, vol. 4, no. 6, Nov. 2005, pp. 2983-2993.

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

[5] H.S. Jo, "Codebook-Based Precoding for SDMA-OFDMA with Spectrum Sharing," *ETRI J.*, vol. 33, no. 6, Dec. 2011, pp. 831-840.

[6] V.J. Mathews and G.L. Sicuranza., *Polynomial Signal Processing*, New York: John Wiley & Sons, Inc., 2000.

[7] ITU-R, "Calculation of Free-Space Attenuation," Rec. P. 535-2, ITU, 1994.