Flexible Bandwidth Allocation Scheme based on Traffic Demands and Channel Conditions for Multi-beam Satellite Systems

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Abstract—**Multi-beam satellite networks can extend the service coverage as deploying the spot beams. It is important to allocate the appropriate resources to multi-beam downlinks to prevent the unnecessary waste of resources due to the inherent limitations of them, such as power, bandwidth, and even the use of a spot beam. In this paper, we propose a resource management technique adjusting the bandwidth of each beam, in which the difference between the traffic demand and allocated capacity is minimized. This represents a reasonable solution for flexible bandwidth allocation considering a trade-off between the maximum total capacity and fairness among the spot beams with different traffic demand. In addition, in order to improve the total system capacity, we present the flexible beam management algorithm. Meanwhile, the proposed flexible bandwidth allocation scheme does not yield a closed-form solution for the beam profile in terms of bandwidth. Therefore, we present the method to find optimal beam bandwidth via heuristic search.**

Keywords-resource management; multi-beam satellite; beam selection; flexible bandwidth allocation; proportional fairness

I. INTRODUCTION

A Multi-spot beam satellite will play important role in the future satellite communication systems due to its inherent characteristics, such as support to high data rate to small user terminals, flexibility in network topology, and etc. In other words, it can provide the high total system capacity by efficiently constructing the flexible service networks. In this environment, it is important to prevent an unnecessary waste of resources and maximize the effectiveness of their utilization, because these satellite resources such as power, bandwidth, and the use of a spot beam are expensive and scarce [1].

In general, each spot beam has different traffic demand as well as channel condition depending on the service requirement and location 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 condition across all spot beams. As a part of this effort, the allocated capacity of each beam should be changed adaptively according to the time-variant traffic distribution over multi-beam satellite downlinks.

In order to improve the performance of those systems, the efficient resource management techniques have proposed. In previous researches, 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 [2][3]. 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 proposed the flexible bandwidth allocation (FBA) scheme which has how to assign a different number of narrowband channels per beam to maximize the spectral efficiency [4]. It can give a reasonable solution between the maximization of total capacity and the support of proportional fairness among the beams.

In general, it is well known that the maximum total capacity can be achieved by water-filling approach. However, it cannot allocate more resource to the spot beam which requires the high demand under purpose of maximization of total system capacity. In other words, it is a vulnerable system to the support of proportional fairness, since it does not reflect the situation whose each spot beam is put on different condition. In this regards, the FBA scheme proposed in [4] allocates more bandwidth to beam with higher traffic demand and channel condition to achieve the proportional fairness over spot beams, but loses some total capacity. In order to compensate the degradation of total system capacity for proposed FBA scheme, we present how to give the highest priority to the active beam for multi-beams within a satellite coverage area to improve the total system capacity. Meanwhile, since the beam profile by the proposed FBA scheme dose not yield a closed-form solution in terms of bandwidth of each beam, we present the method to obtain optimum beam bandwidth via heuristic search.

II. MULTI-BEAM SATELLITE NETWORK INCORPORATING SELECTIVE ACTIVE BEAM SCHEME

Fig. 1 shows the system model of the multi-beam satellite network which can utilize the effective dynamic resource allocation technique using selective active beam scheme. In this network, a multi-spot beam satellite and an ensemble of cell sites with spot beams are deployed. Each

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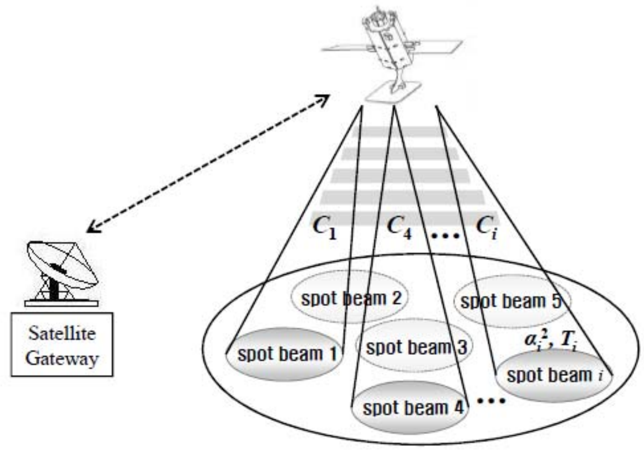

Figure 1. Multi-beam satellite network incorporating selective active beam scheme

of the beams requires the real traffic demand which is distributed with non-uniform and time-varying. For example, as shown in the Fig.1, the spot beam has the different traffic T_i and weather-induced signal attenuation α_i^2 ($\leq$1). Then, the multi-beam satellite allocates the resources to all beams or some of whole beams considering their conditions. The concept of the flexible resource allocation techniques is that the satellite allocates the appropriated amount of resources as power, bandwidth, and use of a spot beam. In this paper, we adjust the bandwidth of beam and use of beam itself to construct the flexible networks.

Using time sharing for Gaussian broadcast channels [5], we can obtain the Shannon bounded capacity C_i for the ith beam as follows.

$$C_i = W_i \log\left(1 + \frac{\alpha_i^2 P}{W_i N_0}\right), \tag{1}$$

where P, N_0 mean the transmit power used and noise power density for ith beam. In addition, W_i is the allocated bandwidth that can be adjusted to optimize resource use.

In this paper, we mainly consider that downlink channels have the property of rainfall attenuation, which are slow fading events. Also we assume inter-beam interference that can be induced from adjacent beams is negligible by considering very narrow beams over a large number of cells.

III. PROPOSED FLEXIBLE BEAM BANDWIDTH ALLOCATION

A. *Flexible Bandwidth Allocation of Multi-beam satellite System*

We proposed the dynamic bandwidth allocation scheme sacrificed total capacity somewhat, but nevertheless, can achieve more proportional fairness for all spot beams with different traffic demands [4]. It is aimed at the best case when available capacity matches demand under the assumption of a simplified model. In addition, we assumed that the total system capacity cannot meet the total traffic demand in order the study on effective resource management deserves sufficient consideration under a communications environment with a scarcity of resources. In this regards, 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 given below.

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

$$\text{subject to} \quad C_i = W_i \log_2\left(1 + \frac{\alpha_i^2 P}{W_i N_0}\right) \leq T_i \text{ for } i=,2,\ldots,N \tag{3}$$

$$\sum_{i=1}^{N} W_i \leq W_{total}, \tag{4}$$

where N is the number of spot beams. The first constraint in (3) indicates that the ith 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 $L(W_i,\Lambda)=\sum_i(T_i - C_i)^2+\Lambda(\sum_i W_i - W_{total})$ [6], we can derive the optimum beam profile in terms of W_i as follows:

$$T_i - C_i = \frac{\frac{\Lambda \ln 2}{2}\left(1 + \frac{\alpha_i^2 P}{W_i N_0}\right)}{\ln 2\left(1 + \frac{\alpha_i^2 P}{W_i N_0}\right)\log_2\left(1 + \frac{\alpha_i^2 P}{W_i N_0}\right) - \frac{\alpha_i^2 P}{W_i N_0}}, \tag{5}$$

where Λ is a Lagrange multiplier that is determined by the total bandwidth constraint of (4). Nonnegative Λ means that that the determined bandwidth by (5) satisfies the constraint $C_i \leq T_i$ 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 in order to obtain the optimum bandwidth W_i in terms of traffic demand T_i. Later, in the section *C*, we handle the process to obtain the final bandwidth via heuristic approach method.

The proposed flexible bandwidth allocation scheme sacrificed total capacity somewhat, but nevertheless, can achieve more proportional fairness for all spot beams with different traffic demands. We can confirm this by comparing the performances such as the throughputs and values of $\sum_i (T_i-C_i)^2$ between the proposed scheme and conventional water-filling method which can achieve the maximum total capacity in the simulation results.

B. Active Beam Selection Algorithm for Spot Beams with Different Conditions

A concept of the proposed active beam selection scheme select the small number of K active beams among the $N(>K)$ multiple beams in order to allocate the resource. So as to derive the active beam selection algorithm, we adopt another constraint as follows.

$$W_i \geq 0, \tag{6}$$

This constraint (6) is added to see which users should be served with non-zero bandwidth and to consider the beam selecting algorithm. We apply again the Lagrangian function so that it can reflect the additional constraint in the same way as the previous section.

$$L(W_i,\Lambda,s_i)=\textstyle\sum_i(T_i-C_i)^2+\Lambda(\sum_i W_i-W_{total})+\sum_i s_i(-W_i) \tag{7}$$

where s_i is the extra Lagrange multiplier. By differentiating with respect to W_i, we can derive the following (8).

$$\frac{\partial L(W_i,\Lambda,s_i)}{\partial W_i}=\frac{\partial \sum_i (T_i-C_i)^2}{\partial W_i}+\Lambda-s_i \tag{8}$$

where, Lagrangian multiplier $s_i(\geq 0)$ is for $-W_i\leq 0$, and is for the total bandwidth constraint. The Kuhn-Tucker condition [5] can yield $s_i = 0$ if $W_i > 0$, and $s_j \geq 0$ if $W_j = 0$. First, applying this condition to (8), we have the $s_i = 0$ and $\partial L/\partial W_i|_{W_i= W_i^*} = 0$ at the optimum beam bandwidth $W_i^* > 0$. From (8), we obtain as follow.

$$-\left.\frac{\partial \sum_i (T_i-C_i)^2}{\partial W_i}\right|_{W_i=W_i^*}=\Lambda < -\left.\frac{\partial \sum_i (T_i-C_i)^2}{\partial W_i}\right|_{W_i=0} \tag{9}$$

where the inequality is valid by concavity of capacity C_i. Next, when the optimal bandwidth is $0(W_j^* = 0)$ for jth beam, we have the $s_j \geq 0$ and $\partial L/\partial W_j|_{W_j=0} = 0$. Then again from (8),

$$-\left.\frac{\partial \sum_i (T_i-C_i)^2}{\partial W_j}\right|_{W_j^*=0}+s_j=\Lambda \geq -\left.\frac{\partial \sum_j (T_j-C_j)^2}{\partial W_j}\right|_{W_j=0} \tag{10}$$

By comparing the right sides of (9) and (10) with respect to common Λ, we can find the optimum policy to select K active beam with highest value of

$$-\left.\frac{\partial \sum_i (T_i-C_i)^2}{\partial W_i}\right|_{W_i=0}=-\left.\frac{\partial \sum_i \left(T_i^2-2T_iC_i+C_i^2\right)}{\partial W_i}\right|_{W_i=0}$$

$$=T_i\left(\log_2(\alpha_i^2)-\frac{1}{\ln 2}\right). \tag{11}$$

TABLE I.
A SET OF UPDATING PROCESS TO OBTAIN OPTIMUM BANDWIDTH

Step (1)	Save the sum of the W_i^{iter} $(=\sum W_i^{iter})$.
Step (2a)	If $\sum W_i^{iter} > W_{total}$, then set $\Lambda_{min}=\Lambda$ and let $\Lambda=(\Lambda_{min}+\Lambda_{max})/2$.
Step (2b)	If $\sum W_i^{opt} < W_{total}$, then set $\Lambda_{max}=\Lambda$ and let $\Lambda=(\Lambda_{min}+\Lambda_{max})/2$.
Step (3)	Recalculate W_i^{iter} and $\sum_i W_i^{iter}$ using the updated Lagrange multiplier Λ instead of Λ_0 and (5).
Step (4)	Carry out the process of Step (2), (3) iteratively until $\sum_i W_i^{iter} = W_{total}$

In other words, in order to select the K active beams among the N spot beams with traffic demand, we only need to investigate the value of (11) across all spot beams. It can deem that the higher traffic demand and better channel condition for whole beams give the highest priority to the active beam.

C. Heuristic Approach Method to optimum bandwidth for ith Beam

As we mentioned earlier, since the beam bandwidth profile of (5) is not yield close-form solutions, in order to obtain the optimum bandwidth of the ith beam, we apply an intuitive and heuristic approach to decode the relationship between traffic demands and the proposed beam profile in terms of W_i. From (5), we can derive a formula for the Λ as follow.

$$\Lambda=\frac{2(T_i-W_i\log_2(1+\Delta_i))}{\ln 2}\left[\frac{\ln 2(1+\Delta_i)\cdot\log_2(1+\Delta_i)-\Delta_i}{(1+\Delta_i)}\right], \tag{12}$$

where $\Delta_i=\alpha_i^2P/W_iN_0$. First, considering the Lagrangian multiplier which is determined according to the total bandwidth constraint, the initial value Λ_0 for Λ is obtained. In order to obtain the initial value Λ_0, we assume that the total bandwidth would be allocated to a spot beam in which the traffic demand corresponding to the sum of the traffic demands across the all beams $(\sum_i T_i=T_{sum})$ occurred. Therefore, T_{sum} and W_{total} are put into T_i and W_i of (12), respectively. Then, using binary search approach as rule of thumb, we set a range of $\Lambda_{min}=\Lambda_0/l$ and $\Lambda_{max}=\Lambda_0\cdot l$ in which the final value Λ^{opt} can be existed. The value of l is a constant of larger than 2. After determining the initial values of Λ_{min} and Λ_{max} from Λ_0, and inserting the Λ_0 to (5), the initial values of W_i (we refer to this value as W_i^{iter}) can be calculated. Then, the procedure used to update these values as well as to find the optimum bandwidth for each beam is as follows.

According to the above process, we finally obtain the optimum bandwidth for each beam when the Lagrangian

TABLE II. SYSTEM PARAMETERS IN THE SIMULATION FOR FIG. 2

Parameters	*Values*
Number of spot beams, N	20
Number of active beams, K	15
Total system bandwidth	500 MHz
On board EIRP	80.33dBW
Free-space path loss [7], f_s=2.5GHz	191.53 dB

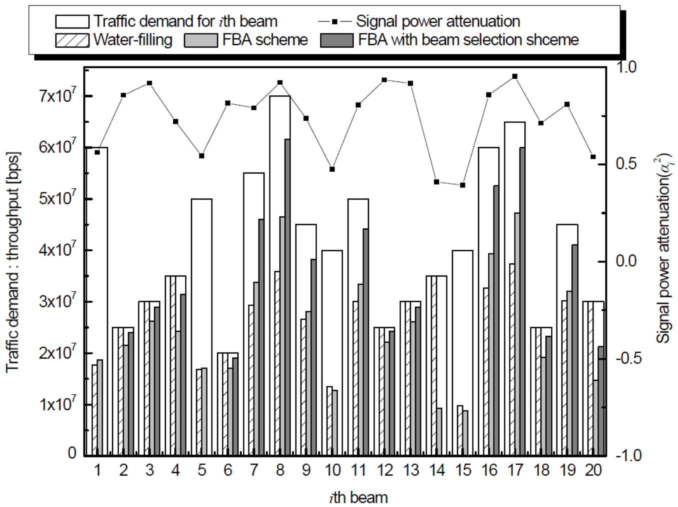

Figure 2. The comparison of throughput of ith beam for water-filling, FBA scheme and FBA scheme with selective beam allocation

multiplier Λ reaches its final value Λ^{opt}.

IV. SIMULATION RESULTS

This section presents the simulation results. We evaluate the performance of the proposed bandwidth allocation schemes using a simple simulation model. In the simulation, we assume that an S-band GEO satellite channel with non-uniform signal attenuation $\alpha_i^2(\leq 1)$ which is generated randomly for the simulation. Also, on-board transmission power is uniformly distributed by the number of spot beams, and we set the l factor to 10 in order to determine the range for searching the final optimal Λ. In this paper, 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 focused on the long-term average gain with respect to the Shannon capacity and spectral efficiency. Table 2 represents the system parameters used in our simulation model for fig. 2.

Fig. 2 shows the capacity distributions of spot beams that are allocated by water-filling method and proposed FBA schemes (including the selective active beam algorithm), respectively. For the simulation, the instantaneous traffic demand is exponentially distributed between 20Mbps and 70Mbps; the maximum traffic demand is 70Mbps.

As we noted earlier, the water-filling scheme can achieve the maximum total capacity. As confirmed in table 3, indeed,

TABLE III. THE COMPARISON OF TOTAL THROUGHPUTS

Allocation Scheme	Total throughput
Water-filling method	534.64 Mbps
FBA scheme in [4]	498.32 Mbps
FBA with beam selection scheme	544.91Mbps

TABLE IV. COMPARISON OF THE TOTAL SUM OF $\sum_i (T_i\text{-}C_i)^2$

Allocation Scheme	$\sum_i (T_i\text{-}C_i)^2$
Water-filling method	7.0797E15
FBA scheme in [4]	6.9144E15
FBA with beam selection scheme	4.2376E14

the water-filling scheme can achieve greater total system capacity than the proposed flexible bandwidth allocation scheme without beam selection scheme. However, in this paper, 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. In this regard, we focused on the minimization of the gap between supported C_i and T_i, and we can confirm that the proposed scheme coincides more closely to the objective of this resource allocation through a comparison of the total sum of the gaps from a result of table 4.

In addition, in order to compensate the throughput degradation of system capacity, we present the selective active beam scheme in this paper. As shown in table 3, it results in total throughput gain compared to non-selective allocation scheme, i.e. FBA scheme, even with water-filling method. Also, it can be most consistent with our purpose of this resource allocation when comparing the values of $\sum_i (T_i\text{-}C_i)^2$. However, in some cases, it cannot be selected as active beam based on worse channel condition despite the beam with high traffic demand to improve the total system capacity (e.g., ith beams for i= 1, 5, 10, 14, 15 in the Fig. 2). From this result, we can infer that we can achieve more total system capacity, but lose the fairness for some of the beams. In other words, we face a trade-off problem between the maximum total capacity and fairness among the spot beams.

V. CONCLUSION

In this paper, we introduce the flexible resource management techniques according to the traffic distributions and channel conditions for the parallel multi-beam satellite system. This paper studies how to allocate the active beam considering trade-off problem between maximum total capacity and proportional fairness among beams with traffic demand by minimizing difference between beam traffic demands and allocated beam capacities. The proposed flexible bandwidth allocation scheme sacrifices total capacity somewhat, but nevertheless, can achieve more proportional fairness for all spot beams with different traffic demands. In addition, in order to compensate the degradation of total system capacity for proposed FBA scheme, we present the selective active beam allocation scheme which can achieve the best performance of total system capacity. Meanwhile, since the beam profile by the proposed FBA scheme dose not yield a closed-form solution in terms of bandwidth, we present the method to obtain optimum beam bandwidth via heuristic search.

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