A beam-dominating frequency resource allocation and scheduling scheme for multi-beam satellite system

Xuejian Liu, Kaiming Xu, Fanyi Wu, Jianjun Wu
School of Electronics Engineering and Computer Science
Peking University
Beijing, China
lxj325@126.com

***Abstract*—In this paper, we aim at the characteristics of the large-scale dynamic beamforming system model, and design an overall scheme for beam-dominated resource allocation and beam scheduling. We first propose a channel capacity fairness carrier allocation algorithm based on the beam as the basic unit to allocate frequency resources between beams, and then perform carrier allocation between users according to the channel demand ratio. Simulation results show that, under the condition of sufficient hardware resources, this scheme can achieve higher user communication satisfaction than the fixed beam resource allocation scheme.**

Keywords—multi-beam satellite, dynamic beamforming, beam scheduling, frequency resource allocation

I. Introduction

The multi-beam technology is widely used in nowadays satellite industry. It can effectively improve the utilization of the frequency band, greatly increase the communication capacity of the system, and can adaptively adjust the beam shape to suppress related interference, which can greatly improve the quality of satellite communication [1].

The early multi-beam satellite antennas were mainly fixed multi-beam antennas, which is the simplest form of Smart Antenna. The structure is relatively simple and the beamforming algorithm is not too complicated. The advanced form of smart antenna is adaptive array antenna [2]. However, the traditional multi-beam satellite communication is facing to some challenges. Firstly, the co-frequency interferences among adjacent beam cells are inevitable. The smaller the beam interval is, the more serious the interference will be. Thus, the channel quality will deteriorate rapidly. Secondly, as the number of beams increases, the complexity of the beamforming network will increase greatly, the consumption of hardware resources will continue to increase and the cost will get higher.

In recent decades, with the rapid technique improvement of multi-beam satellite system, the user-centric service design fashion was introduced in the satellite industry. The concept of single-user in single-beam was proposed in [3], and the corresponding adaptive phased array antenna technology has been widely discussed. Furthermore, a well-tuned frequency resources allocation on multi-beam satellite can effectively improve the system capacity and service quality [5] [6].

In this paper, we discuss the corresponding beam resource allocation and scheduling solution on a large-scale dynamic beamforming-based multi-beam satellite concept system in order to improve the overall resource efficiency of the system.

II. System model

As the supplement and extension of the terrestrial cellular system, there only exist a small fraction of active users in the satellite coverage in most cases. In such a scenario, the conventional multi-beam coverage pattern has the disadvantages of lower beam utilization and lower resource efficiency. Thus, we introduce a conceptual system model with dynamic beam forming and coverage in the entire domain, as shown in Fig.1.

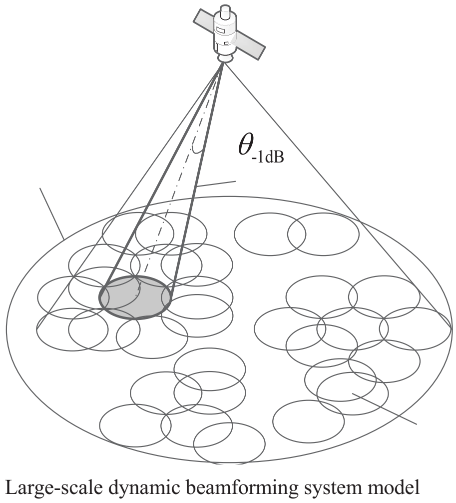

Fig. 1. Large-scale dynamic beamforming system model

In such a dynamic beam satellite system, new users may access it anytime and anywhere, since the user may stay at any position. Although the system does not require real-time beam coverage of the entire area, it must have the capability of global coverage and switch to the form of global coverage when necessary. In other words, this system needs to integrate global coverage capabilities with user-centric beamforming mechanisms.

2021 IEEE International Conference on Power Electronics, Computer Applications (ICPECA) | 978-1-7281-9004-4/20/$31.00 ©2021 IEEE | DOI: 10.1109/ICPECA51329.2021.9362526

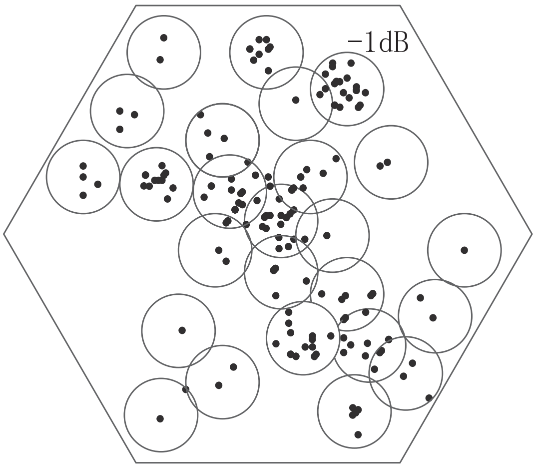

Fig. 2. Example of target beam distribution under user distribution

A large-scale dynamic beamforming system scenario is illustrated as in Fig.2. The total number of users in this system is K, and the users are randomly distributed on the ground. The channel capacity requirement of the user is set to $\mathrm{D}_i, i=1,2,3,\cdots K$. The total number of subcarriers is Q, and the carrier bandwidth is B; the channel uses a Gaussian channel model, and the noise power spectral density $N_0(f)$ is constant. The value of K in this model may be large, and the user channel quality within the coverage of the same beam will vary with the distance of the user from the center of the beam.

III. BEAM-DONMINATING RESOURCE ALLOCATION AND SCHEDULING SCHEME

The allocation of large-scale dynamic beamforming resource schemes is dominated by beams. Firstly, the beam is used as a unit for subcarrier allocation. Secondly, within each beam, subcarriers are allocated twice according to different user channel requirements. Finally, the water injection method is used for power allocation for each user. This solution greatly reduces the complexity of the user-centric resource allocation strategy on the premise of ensuring user service quality.

A. Target beam determination process

Traditionally, there is a -3dB gain attenuation at the edge in contrast to the center of beam. In order to improve user service quality, the most direct way is to keep the user at the center of the beam coverage area at any time. To this end, the system reduces the beam edge to a -1dB attenuation range, that is, when the user leaves the -1dB coverage range of the original beam, a new beam needs to be generated to serve the user.

We redefine the beam range as a -1dB attenuation edge. To determinate the target beams, a specific process is given below:

(1) Assume that the user set is θ and the serving user set of target beam i is φ_i. All users in θ are sorted according to the channel demand from high to low. The user with the largest channel demand is selected, and its position is the center position of the new target beam i, And add all users in θ that are within the -1dB coverage of this beam to set φ_i, and move these users out of θ.

(2) Repeat step (1) until θ is empty.

(3) Recalculate the channel demand of the target beam: Define the user k channel demand as d_k and the target beam i channel demand as D_i, then $D_i = \sum_{k\in\varphi_i} d_k$.

Approximately, there is only one user in the beam coverage area located at the center of the beam and the channel demand is D_i and the number of users is the same as that of beams, as shown in Fig.3.

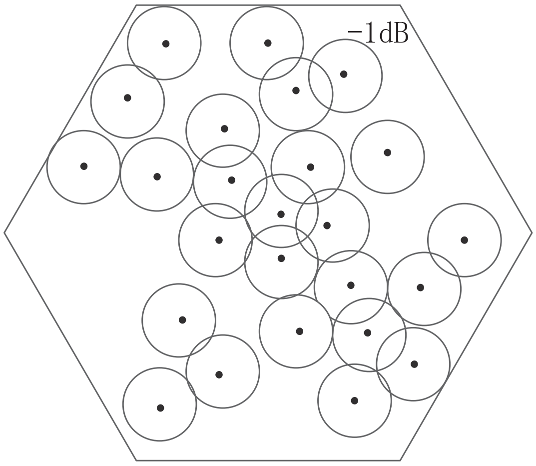

Fig. 3. Example of target beam setup result of one-user one-beam determination process

B. Frequency resource allocation algorithm

In order to ensure that the actual channel capacity of different users meets the needs as much as possible, the optimization objective function is designed as follows:

$$\max_W(\min_{1\le i\le K}(R_i(W)-D_i))$$

Among them, D_i is the channel demand of beam i, and $(R_i(W)-D_i)$ is the difference between the actual channel capacity of the beam and the required channel capacity, that is, at the current moment, the user with the largest gap between the required channel capacity in all beams has priority to allocate the best subcarrier right. The selection of W_k matrix needs to satisfy the following constraints:

$$\sum_{i=1}^{M} w_i^H w_i \le P_{total}$$

That is, the sum of the power of all user subcarriers cannot exceed the total system power. The value of w_{ij} must meet the following requirements:

$$|w_{ij}|^2 = \{0, P_0\}, i=1,2,3,\cdots,K; j=1,2,3,\cdots,Q$$

Among them, the value of w_{ij} is 0, which means that the subcarrier is not selected, the value of w_{ij} is P_0, which means that the subcarrier is selected, and the carrier power is P_0.

This solution uses the difference between $R_i(W)$ and D_i instead of the ratio as the system optimization parameter. In order to ensure the fairness of each user, the minimum difference maximization algorithm is used for related optimization. The specific operation flow of the frequency allocation algorithm is as follows:

- [a]. Initialization phase:

(1) All beams are ordered from high to low according to the size of the communication demand, which meets $D_i \geq D_{i+1} \mid i = 1,2,3,\cdots,K$.

(2) According to the priority order, assign an optimal subcarrier to each beam in turn.

(3) Let $k = 1$.

(4) Find the subcarriers with the best channel conditions and the highest signal-to-noise ratio in the $SINR$ matrix of beam k, that is $| SINR_{k,n} | \geq | SINR_{k,j} | |_{j=1,2,3,\cdots,Q}$, and assign them to beam k;

(5) Let $k = k+1$.

(6) Repeat step (2) until the position at $k = K$.

- [b]. Carrier allocation phase:

(1) Find beam m in all beams, satisfy $(R_m(W) - D_m) \leq (R_i(W) - D_i) |_{m=1,2,3,\cdots,M}$.

(2) In the $SINR$ matrix of beam m, find the subcarrier with the best channel quality and the highest $SINR$ ratio, that is $| SINR_{m,n} | \geq | SINR_{m,j} | |_{j=1,2,3,\cdots,Q}$, and assign it to beam m;

(3) Recalculate the actual channel capacity and repeat steps (1) (2) (3) until $\sum_{i=1}^{K} w_i^H w_i > P_{total}$.

It can be seen from the specific steps of subcarrier allocation that this solution assigns the best subcarriers to the user with the lowest satisfaction first, which increases the communication capacity of the user and makes the channel resource allocation relatively fair.

C. Dynamic beam scheduling

The principle of the beam scheduling algorithm in this scheme is: When a user's location and channel requirements change, if the original beam and frequency allocation scheme is used to continue to serve it, and the user's minimum communication capacity requirements can be met, the beam information and resource allocation results will not be changed. In other words, only when the original beam and resource allocation cannot meet the user's communication quality requirements, readjustment of beam distribution or system resources is considered. This principle can avoid unnecessary updates to the system caused by too many users and small changes.

The beam scheduling will be executed according to the following scenarios. We use α to indicate that the minimum requirements for communication quality can be achieved with the original beam allocation scheme, and use β to indicate that the original resource allocation scheme can be used to meet the requirements. Assuming that the original beam number of user k is n, we will give a specific dynamic beam scheduling scheme for this system:

(1) Scenario 1: When a new user access, if there is beam coverage at the user's location, refer to scenario (4); if there is no beam coverage, a new beam is generated and system resource allocation is re-allocated.

(2) Scenario 2: The user moves out of beam n and does not move within the coverage of any other beams: If α and β are satisfied, no adjustment is made. Otherwise, a new beam needs to be generated, and it is determined whether or not β is satisfied, and if it is not satisfied, the system resource allocation is performed again.

(3) Scenario 3: The user moves out of beam n and moves into the coverage of beam m: the original resources of user k are directly moved to beam m and allocated to user k for use.

(4) Scenario 4: The original beam channel demand changes due to user movement or user channel demand changes: Including three cases of new user access, user removal, and user demand changes, If α and β are satisfied, no adjustment is made; otherwise, the existing frequency and power resources of the beam are redistributed between users to determine whether the requirements are met; if not, system resource allocation is re-allocated.

IV. Numerical analysis and simulation verification

A corresponding simulation verification is performed to validate effectiveness of the above proposed scheme, while comparing with a fixed beam resource allocation scheme which has a cell frequency reuse factor of 3.

TABLE I. Simulation parameter

Parameter	Value
Total number of users	1000-10000
Total bandwidth	500MHz
Total number of subcarriers	256
Total power cap	2000w
Subcarrier power	2w

Define the user satisfaction ratio as:

$$\beta = \frac{\sum_{i=1}^{K} R_i(w)}{\sum_{i=1}^{K} D_i}$$

The simulation results are shown in the following Fig.4. As is shown, the proposed scheme outperforms the traditional fixed beam scheme in terms of user satisfaction ratio. This is because that we take the influence of different channel requirements between users on the system communication capacity, and the beam with the largest channel capacity difference selects the best subcarrier first.

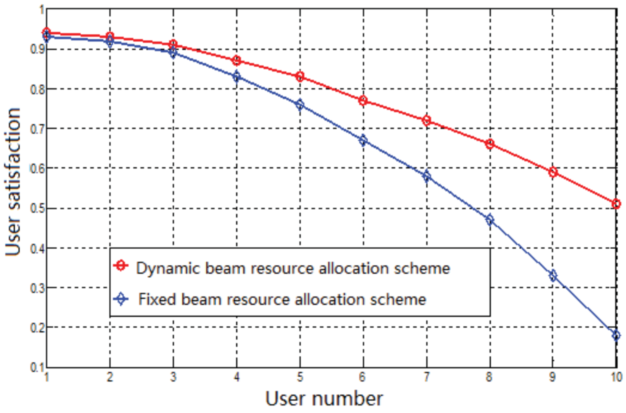

Fig. 4. Comparison of user satisfaction ratio

Considering the resource utilization under the same number of beams, the spectrum utilization efficiency is defined as:

$$\eta = \frac{\sum_{i=1}^{K} R_i(w)}{\sum_{i=1}^{K} B_i}$$

The simulation results are shown in the following Fig.5. It can be observed that the proposed scheme also has better performance in terms of spectrum utilization efficiency than fixed beam resource allocation scheme. However, if there are relatively many users, the former will use more hardware resources.

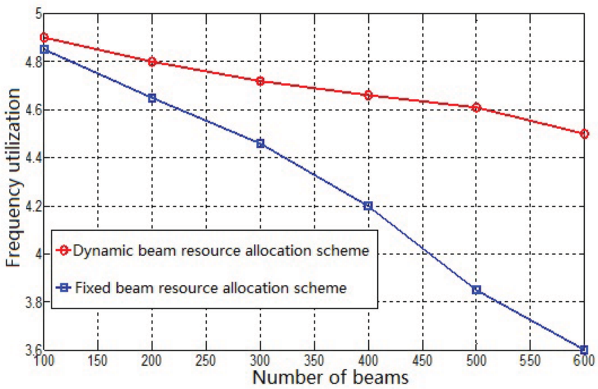

Fig. 5. Spectrum utilization comparison

V. Conclusion

In this paper, we aim at the large number of users in a large-scale dynamic beamforming system, and propose a beam-dominated resource allocation scheme. The proposed scheme consists of 3 procedures, including target beam determination, frequency resource allocation, and dynamic beam scheduling. Simulation results show that, under the condition of sufficient hardware resources, our proposed scheme can achieve a higher user communication satisfaction than the fixed beam resource allocation scheme.

Acknowledgement

This article was supported by the National Natural Science Foundation of China # 61371073.

References

[1] De Santis, Pietro. "Non-regenerative multibeam satellite communications system with FDMA access and SSTDM connectivity." U.S. Patent No. 5,274,627. 28 Dec. 1993.

[2] Fenn, A.J. “Evaluation of adaptive phased array antenna, far-field nulling performance in the near-field region.” Antennas and Propagation, IEEE Transactions, VOL.38, No.2, 1990.

[3] T. Gebauer, H.G. Gockler, "Channel-individual adaptive beamforming for mobile satellite communications," IEEE Journal on Selected Area in Communications, vol.13, no.2, pp.439-448, Feb. 1995..

[4] Baracelo-Llado J.E, Vazquez-Castro M.A. Distributed power and carrier allocation in multibeam satellite uplink with individual SINR Constraints. IEEE Global Telecommunications Conference, 2009, 5(3): 1~6.

[5] J.P. Choi, V.W.S.Chan. Optimum power and beam allocation based on traffic demands and channel conditions over satellite downlink. IEEE, 2005, 2(6): 2983~2993.