Interference-aware Spectrum and Power Coordination in Satellite-aided Cell-free Massive MIMO System

Mingliang Pang[1], Chaowei Wang[1](✉), Danhao Deng[1], Yehao Li[1], Weidong Wang[1], and Lexi Xu[2]

[1] Beijing University of Posts and Telecommunications, Beijing, People's Republic of China
{pangmingliang,wangchaowei,dengdanhao,liyehao,wangweidong}@bupt.edu.cn
[2] China United Network Communications Corporation, Beijing, People's Republic of China
xulx29@chinaunicom.cn

Abstract. In this paper we construct a hybrid architecture that combines terrestrial cell-free massive MIMO system and multi-beam satellite communication system to maximize the throughput within the coverage. We propose an interference-level based user selection algorithm to divert terrestrial users with stronger interference to satellite service, thereby reducing the total system interference. For satellite users, to further increase the system throughput, we use the co-frequency across beams, which include two steps, inter-beam and intra-beam resource allocation. The former uses soft frequency reuse and the latter is allocated based on water-filling algorithm. The simulation results show that the proposed satellite-aided cell-free system has a significant improvement in throughput compared with the traditional system. At the same time, the throughput of satellite users is also improved compared with the traditional frequency reuse scheme.

Keywords: Cell-free massive MIMO · Multi-beam satellite · Frequency reuse · Resource management

1 Introduction

As one of the core technologies of the 5th generation mobile communication, the massive multiple-input multiple-output (MIMO) technology deploys dozens to hundreds of antennas in the base station (BS) [1]. The antenna can obtain strong array gain, diversity gain and spatial multiplexing gain, which can provide services for multiple mobile terminals (MT) on the same time-frequency resource block and greatly improve the system spectrum efficiency. However, with the

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further densification of cells, inter-cell interference has become a major bottleneck limiting the performance of massive MIMO systems, which seriously affects the performance of cell-edge MT [2]. In order to suppress the above-mentioned interference and provide homogeneous service for all MTs, the cell-free massive MIMO system emerges as the times require. In this system, the traditional BS is replaced by numerous distributed access points (AP), and the same MT can be served by multiple APs on the same time-frequency resources [3]. This technology makes the MT break through the constraints of the cell boundary, and the MT is located in the center of the cell [4]. Compared with traditional cellular massive MIMO networks, cell-free massive MIMO has obvious advantages. It has large energy efficiency, which is brought about by the high array gain. Due to the strong macro diversity gain, cell-free massive MIMO can considerably improve the achievable sum-rate [5]. Furthermore, it can provide high throughput, reliability, and energy efficiency with simple signal processing [6]. In addition, the average distance between the closest antennas and an arbitrary MT is substantially reduced by invoking a large number of distributed antennas, which makes the deployment of cell-free massive MIMO more flexible and cost-effective [7].

In addition to cell-free massive MIMO, satellite networks are also an important part of 5G and even 6G. The satellite system has developed from the initial global beam and regional beam to the current multi-spot beam. The emergence of spot beam technology is one of the important advancements in the improvement of modern satellite communication capabilities. The spread of multi-beam antennas increase drastically the number of users that can potentially be served by single satellite [8]. Multi-beam satellites (MBS) have been widely used not only because the resource utilization rate of satellite systems can be effectively improved through the inter-beam frequency reuse technology [9], but also because it raises possibility for the sharing the satellite frequency with other radio network including terrestrial radio system [10]. Additionally, the introduction of phased array antenna technology can allow for reconfigurable beam numbers, aiming points, and beamforming to further enhance spot beam capabilities [11]. As multi-beam satellite communication system has the advantages of extensive coverage, high beam gain, small user terminals and high frequency utilization, it plays an irreplaceable and important role in mobile and emergency communication scenarios over a large area in complex environments such as floods, earthquakes and so on [12].

In this paper, we combine terrestrial cell-free massive MIMO system with satellite network. The terrestrial users and satellite users are distinguished by an interference-based user selection algorithm, and the satellite is used to reduce the interference of the system and enhance the throughput performance of the system. The main contributions of this paper can be summarized as follows:

1. Combining the advantages of cell-free massive MIMO and multi-beam satellite systems, we have established a hybrid communication architecture for satellite-terrestrial integration. The satellite network complements terrestrial communications to enhance the performance of the hybrid system.

2. Based on the interference level between users, a user selection algorithm was designed to classify users into terrestrial and satellite users. Users with higher interference are selected to provide services via satellite, thus significantly reducing the interference in the system.
3. For the resource allocation of satellite users, we split it into two steps, inter-beam resource allocation and intra-beam resource allocation. The former uses soft frequency reuse, and the latter uses water-filling algorithm to allocate power and bandwidth resources. Experimental results show that the proposed resource allocation algorithm can improve the throughput performance of the system.

The rest of this paper is organized as follows. Section 2 describes the work related to satellite-aided cell-free massive MIMO system and the multi-beam satellite resource management. Section 4 provides the user selection algorithm and resource allocation algorithm. Section 5 analyzes the simulation results. Finally, the conclusions are given.

2 Related Work

However, the inter-beam interference problem of multi-beam satellites cannot be ignored. For the problem of inter-beam interference, [8] lists three system characteristics that affect the co-channel interference (CCI) between satellite beams: beam layout, multiplexing scheme and scheduling. Among them, the beam layout depends on the design of the antenna, and the traditional hexagonal grid is being replaced by a more efficient beam layout, such as a square grid [13], which can greatly reduce the CCI by increasing the distance from the center of the same polarized beam. In the multiplexing scheme, the four-color multiplexing mostly adopts the form of 2 sub-bands and 2 polarizations, which has good interference isolation characteristics. If a smaller frequency reuse factor is adopted, the relationship between the increase of the beam bandwidth and the actual achievable system capacity needs to be weighed to ensure that it is beneficial to the satellite system. The third goal of scheduling is efficiency and fairness. Scheduling is usually performed by the beam's gateway, which generally only has local beam information, and the interference generated by other beams is unknown. The current trend is to centrally control the gateway through SatCloudRAN [14] to coordinate processing of all beams, which can better control interference.

In terms of satellite resource management, [15] established a model of maximizing the number of serviceable users under power constraints in a multi-beam satellite network, and proposed an intelligent search algorithm by applying the greedy idea. Compared to an exhaustive search, the algorithm limits the search to the case where the beam exhausts all available energy, thus reducing the computational complexity. Aiming at the optimal power allocation problem based on service matching service in MBS communication system, [16] adopts a two-stage power allocation method based on genetic algorithm and simulated annealing (GA-SA) algorithm to minimize the unsatisfied system capacity (USC). The proposed two-stage approach improves USC while reducing overall power consumption compared to uniform power distribution. In [17], the power allocation problem is formulated as a convex optimization problem, and the inter-beam interference problem is solved by Lagrangian theory and subgradient iteration. The evaluation results show that the algorithm has good performance in terms of delay, bandwidth utilization, capacity and fairness, and has strong robustness in practical applications. In [18], the power allocation problem in the flow matching of multi-beam satellite systems is reduced to an optimization problem, and the convex optimization framework is decomposed into different sub-problems, each sub-problem is executed by a given agent. The conjecture-based multi-agent Q-learning algorithm proposed in the literature is used to search for the optimal power allocation scheme, which improves the communication satisfaction and fairness of the system under the premise of low complexity.

In addition, there is few research on satellite-aided cell-free massive MIMO system. [19] proposes an algorithm for LEO satellite-aided cell-free massive MIMO network that forms an integrated space-terrestrial framework that combines the benefits offered by ultra-dense terrestrial deployment (cell-free massive MIMO) with the large coverage of the LEO satellite segment. The algorithm controls the transfer of users from the ground to the satellite segment, shifting those users who somehow limit the performance of the terrestrial network to the satellite segment, ultimately improving the worst user rate. In [20], the authors propose an optimization framework and a greedy solution for hybrid network architectures that combine a cell-free massive MIMO terrestrial layout with a low Earth orbit satellite segment to maximize the minimum per-user rate in the coverage area. When a single-antenna access point is operated on a surface section or when deployed sparsely, the hybrid network architectures have significant results.

3 System Model

We consider a scenario shown in Fig. 1, in which there is a multi-beam GEO satellite with a cell-free system in each beam, and the satellite and terrestrial access points assist in serving users. Specifically, satellite users and terrestrial users are selected through a suitable user selection algorithm. The terrestrial users are served by access points, and the satellite users are served by the satellite through the gateway station. Since the communication frequency bands used by the ground and satellite are different, the interference between the ground communication system and the satellite communication system can be ignored.

3.1 Terrestrial Communication Model

Duplexing Mode. To exploit the reciprocity of the uplink (UL) and downlink (DL) channels, TDD is the duplex mode adopted in the cell-free massive MIMO system [21]. For channel estimation, both UL and DL pilots can be used.

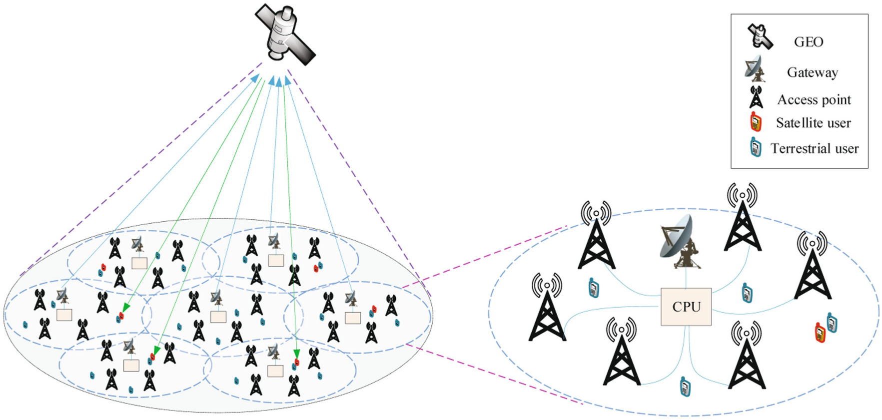

Fig. 1. Satellite-aided Cell-free Massive MIMO System.

Therefore, in the ground satellite fusion network architecture designed in this paper, the duplex mode of the ground cell-free system is TDD. Then, we mainly consider the user's downlink later in this paper.

Signal Model for Downlink Transmission. We consider a cell-free scenario with L APs and K users in this paper. Then, we adopt the compressed-based strategy downlink signal model shown in [22]. The CPU compresses the baseband signal by quantizing the fronthaul links and forwarding them to each AP; hence, the received signal at the ith AP is given as

$$\boldsymbol{x}_l = \sum_{k}^{K} \boldsymbol{w}_{l \cdot k} s_k + \boldsymbol{q}_l, \tag{1}$$

where $\boldsymbol{w}_k = \left[\boldsymbol{w}_{1,k}^{\mathrm{T}}, \ldots, \boldsymbol{w}_{L,k}^{T}\right]^{\mathrm{T}}$ represents the beamforming vector of downlink user k sent by all APs, and $s_k \sim \mathcal{CN}(0,1)$ is the signal for downlink user k. $\boldsymbol{q}_l$ represents the quantization noise which related to the compression noise power of AP.

The channel matrix of user k can be expressed as

$$\mathbf{h}_k = \left[\mathbf{h}_{1,k}^{\mathrm{T}}, \mathbf{h}_{2,k}^{\mathrm{T}} \cdots \mathbf{h}_{L,k}^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{2}$$

where $\boldsymbol{h}_{l,k}^{\mathrm{T}}$ denotes the channel state information matrix from lth AP to kth user. Then, the received signal of downlink user k can be expressed as

$$y_k = \sum_{l}^{L} \mathbf{h}_{l,k}^{\mathrm{H}} \boldsymbol{x}_l + n_k. \tag{3}$$

In Eq. (3), $n_k \sim \mathcal{CN}\left(0, \sigma_k^2\right)$ represents the additive white Gaussian noise. Then, the data rate of user k can be expressed as

$$R_k = \log_2\left(1 + r_k\right) = \log_2\left(1 + \frac{\rho_k \left|\boldsymbol{h}_k^{\mathrm{H}} \boldsymbol{w}_k\right|^2}{\rho_k \gamma_k + \delta_k^2}\right), \tag{4}$$

where

$$\gamma_k = \sum_{k', k' \neq k} \left|\boldsymbol{h}_k^{\mathrm{H}} \boldsymbol{w}_{k'}\right|^2 + \sum_l \mu_l \left\|\boldsymbol{h}_{l,k}\right\|^2 + \sigma_k^2, \tag{5}$$

denotes the interference matrix of user k and δ_k^2 is the additional circuit noise that stems from nonlinearities during baseband conversion and phase offset.

3.2 Multi-beam Satellite System Model

Considering a single multi-beam GEO satellite, the satellite has M beams, there are N users under each beam, the mth user under the nth beam is denoted by (m, n), located at the position of $\Omega_{m,n}$. The total bandwidth of the satellite system is B_{total}, which is evenly divided into N_B sub-channels and the maximum transmit power of the satellite is P_{total}.

Channel Mode. The tth time slot satellite transmits data to the user (m, n) with power $P_{m,n,t}$, denoting the communication link with $[m, n, t]$, the link bandwidth is $B_{m,n,t}$, and $h_{m,n}$ is the gain of the satellite-ground link. Assume that the multi-beam satellite channel matrix is H_{matrix}:

$$H_{matrix} = [h_{1,1}, h_{1,2}, ..., h_{m,n}, ..., h_{M,N}], \tag{6}$$

in which $h_{m,n}$ can be expressed as

$$h_{m,n} = G_t\left(\theta\right) + PL + G_r\left(\varphi\right). \tag{7}$$

In Eq. (7), $G_t\left(\theta\right)$ is the transmit antenna gain of the link, θ is the angle that the user deviates from the beam antenna axis. PL denotes the loss and fading of the signal power due to the channel environment. $G_r\left(\varphi\right)$ is the receive antenna gain of the link and the angle at which the direction of the received signal deviates from the axis of the receiving antenna is denoted by φ.

Problem Formulation. Considering the problem of co-channel interference, the frequency of the user (m, n) at this moment is f, and the co-channel interference $I_{m,n,t}$ can be expressed as

$$I_{m,n,t} = \sum_{\varphi \in \Xi_f and \neq [m,n,t]} P_\varphi h_\varphi, \tag{8}$$

where Ξ_f denotes the set of all co-channel channels with frequency f. $\varphi \in \Xi_f and \neq [m,n,t]$ indicates the channel $[m,n,t]$ causing co-channel interference. P_φ is the data transmission power of the link, and h_φ is the channel gain of the link. The signal-to-interference-noise ratio $SINR_{m,n,t}$ of the link is

$$SINR_{m,n,t} = \frac{P_{m,n,t}h_{m,n}}{I_{m,n,t} + N_0 B_{m,n,t}}, \tag{9}$$

where N_0 is the power spectral density of white Gaussian noise. The data rate $C_{m,n}^t$ of the communication link between the user (m,n) and the satellite in the tth slot can be expressed as

$$C_{m,n}^t = B_{m,n,t}\log_2(1 + SINR_{m,n,t}). \tag{10}$$

Based on Eq. (10), the sum of the system throughput over the time period T is

$$C_{total} = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{t=1}^{T} C_{m,n}^t. \tag{11}$$

Then the complete optimization problem can be formulated as

$$\begin{aligned} &\mathrm{P}: \max C_{total} \\ s.t.\ &C1: \sum_{m=1}^{M}\sum_{n=1}^{N} P_{m,n} \leq P_{total} \\ &C2: \sum_{n=1}^{N} B_{m,n} \leq B_{total} \forall m \end{aligned}. \tag{12}$$

The optimization objective means maximizing the aggregate throughput of the system. Constraint 1 indicates that the total power of all users is not greater than the maximum transmit power of the satellite; Constraint 2 indicates that the total bandwidth of all users in the same beam is not greater than the total system bandwidth.

4 User Selection and Resource Allocation Algorithms

4.1 User Selection Algorithm

User selection algorithm has been designed in the satellite-ground fusion network in [23]. But the algorithm is more complex. On the basis of [23], this paper proposes a user selection algorithm based on interference. Specifically, it can be known from Eq. (5) that the closer the distance between users is, the greater the interference received by the users. Therefore, we use the distance between users to characterize the interference size of users, and select users based on this. The specific algorithm is shown in Algorithm 1.

First, we calculate the distance d_{ij} between user i and user j and sort it in ascending order. Then we take the first element in d_{1j} as the threshold value, and if the distance between the two users is less than this threshold, one of the users is determined as a satellite user. If the number of satellite users obtained by this threshold is exactly the preset number N_S, the algorithm ends. Otherwise, the threshold will be updated and the above operation will be repeated.

Algorithm 1. Interference-level Based User Selection Algorithm

Initial Set the total number of users in each beam N;
Set the number of satellite users in each beam N_S;
Set the distance threshold to $d_G = 0$.
Output The coordinates of ground users and satellite users.
Randomly generate user coordinates based on the number of users;
Calculate the distance d_{ij} between user i and user j based on user coordinates;
Set $k = 1$;
Set the number of satellite users $M = 0$;
for $i = 1 : N$ **do**
  Sort d_{ij} from smallest to largest as D_i;
  $d_G = D_i(k)$;
  for $j = 1 : N$ **do**
    if $d_{ij} < d_G$ **then**
      Determine user j as a satellite user, $M = M + 1$;
    end if
  end for
  if $M = N_S$ **then**
    break;
  else if $M < N_S$ **then**
    Set $M = 0$, $k = k + 1$, jump to 8;
  else
    Set $M = 0$;
    continue;
  end if
end for

4.2 Resource Allocation Algorithm

The inter-beam resource allocation algorithm in this paper is a soft frequency reuse (SFR) based on fractional frequency reuse (FFR). According to [24] the schematic diagram of frequency reuse is shown in Fig. 2.

The left of Fig. 2 illustrates a strict FFR deployment with a beam edge reuse factor of 3. Users inside each beam are assigned a common frequency subband, while the bandwidth of beam edge users is divided across beams according to a reuse factor of N. In general, strict FFR requires a total of $N+1$ subbands. Center users do not share any spectrum with edge users, which reduces interference to center users and edge users.

Although strict FFR reduces the interference between systems, the frequency band utilization rate is relatively low. Based on strict FFR, the right of Fig. 2 illustrates a SFR deployment with a reuse factor of 3 on the beam-edge. SFR allows center users to share sub-bands of edge users in other beams. Because intra-beam users share bandwidth with neighboring beams, they typically transmit at lower power levels than beam-edge users. While SFR is more spectral efficient than Strict FFR, it causes more disturbance to users inside and at the edge of the beam. But we can reduce the interference in the system by controlling the power ratio of center and edge users.

Algorithm 2. Soft Frequency Reuse Based on Water-filling Algorithm (WSFR)

Initial Generate beams and user coordinates;
Based on SFR set the value of R_{center}, N_{block}, N_{sfr} and β ;
Set the water level $h_w = 0$.
Output The number of resource blocks allocated by the satellite user.

Calculate H_{center}, H_{edge} and d according to the user coordinates;
Calculate P_{center} and P_{edge} based on β;
if $d < R_{center}$ **then**
  $i = 1$;
  Sort all central users by H_{center} and the corresponding channel matrix is $\widetilde{H}_{center}$, in which $\widetilde{H}_{center}(1)$ is worst;
  while true **do**
    Let $h_w = k \big/ \widetilde{H}_{center}(i)$;
    Allocate resource blocks with h_w and calculate the number of allocated resource blocks N_{ac};
    if $N_{ac} < N_{sfr}$ **then**
      The remaining resource blocks are divided equally between the central users;
      break;
    else
      Remove the worst channel without allocating resource blocks, $i = i + 1$.
    end if
  end while
else
  $i = 1$;
  Sort all edge users by H_{edge} and the corresponding channel matrix is $\widetilde{H}_{edge}$, in which $\widetilde{H}_{edge}(1)$ is worst;
  while true **do**
    Let $h_w = k \big/ \widetilde{H}_{edge}(i)$;
    Allocate resource blocks with h_w and calculate the number of allocated resource blocks N_{ae};
    if $N_{ae} < N_{block} - N_{sfr}$ **then**
      The remaining resource blocks are divided equally between the edge users;
      break;
    else
      Remove the worst channel without allocating resource blocks, $i = i + 1$.
    end if
  end while
end if

The intra-beam resource allocation is based on the water-filling algorithm, and the system resource blocks are adaptively allocated mainly according to the user channel state information. Users with good channel status are allocated more resource blocks, and users with poor channel status are allocated fewer resource blocks, thereby maximizing the total throughput. The complete resource allocation algorithm for satellite users is shown as Algorithm 2.

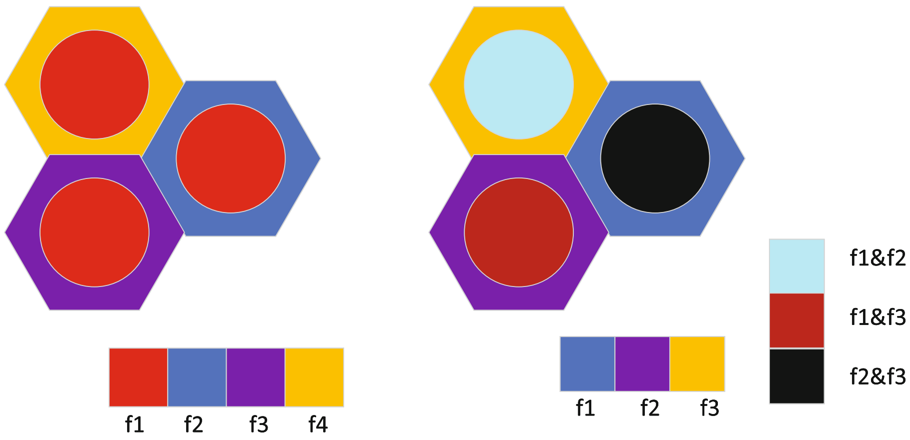

Fig. 2. Strict FFR (left) and SFR (right) resource allocation.

In Algorithm 2, R_{center} is the center radius. N_{block}, N_{sfr} denote the total number of resource blocks and number of central user resource blocks respectively. β indicates the ratio of central user power to total power and h_w is the water level of the water-filling algorithm. k is a constant that controls the water level. The channel state information of central users and edge users are indicated by H_{center} and H_{edge} respectively. d presents the distance between users and beam center. P_{center} and P_{edge} refer to the power of resource blocks occupied by central users and edge users.

5 Simulation Results and Analysis

In this section, simulation experiments are carried out for the algorithm proposed in the Sect. 4 . The main simulation parameters are shown in Table 1.

Table 1. Simulation Parameters.

Parameter	Value
Terrestrial users per beam N_T	500
Satellite users per beam N_S	50
Terrestrial channel bandwidth B_T	10 MHz
Satellite channel bandwidth B_S	30 MHz
Power of AP P_T	10 W
Power of Satellite P_S	200 W
Number of beams N	7
Beam radius R	125.26 KM

We compare the throughput performance using three-color, four-color, same frequency, FFR, USFR and WSFR. Three-color multiplexing refers to dividing the entire frequency band of the system into 3 orthogonal sub-bands, each beam sharing one of the 3 sub-bands, and different frequency bands are specified between adjacent beams, and uniform allocation is used for resource allocation within beams. Four-color divides the entire frequency band of the system into 4 orthogonal subbands on the basis of three colors. Same frequency means that each beam uses the same frequency band and the resource allocation within the beam is also uniformly allocated. FFR means inter-beam using FFR intra-beam using water-filling algorithm to allocate resources. USFR indicates that SFR is used for resource allocation between beams, and uniform allocation is used for resource allocation within beams. WSFR represents the resource allocation algorithm for satellite users proposed in this paper, that is, SFR is used for resource allocation between beams, and water-filling algorithm is used for resource allocation within beams.

The throughput comparison under different central area radii R_{center} is shown in Fig. 3. The throughput of our proposed WSFR algorithm first increases and then decreases as R_{center} increases. This is because when R_{center} is small, there are few central users in the beam, which affects the performance of the system. When R_{center} is large, there will be few users at the edge of the system, which will waste resources and degrade the performance. At the same time, no matter how R_{center} changes, WSFR always outperforms FFR and USFR. This is because WSFR improves the efficiency of frequency utilisation between beams compared to FFR and optimises the scheduling of resources for users within the

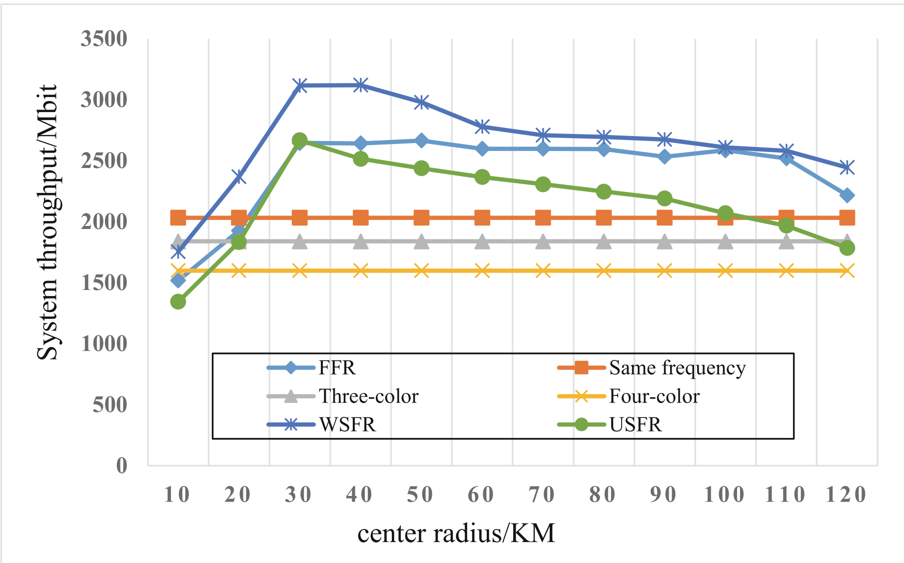

Fig. 3. Comparison of system throughput under different center radii.

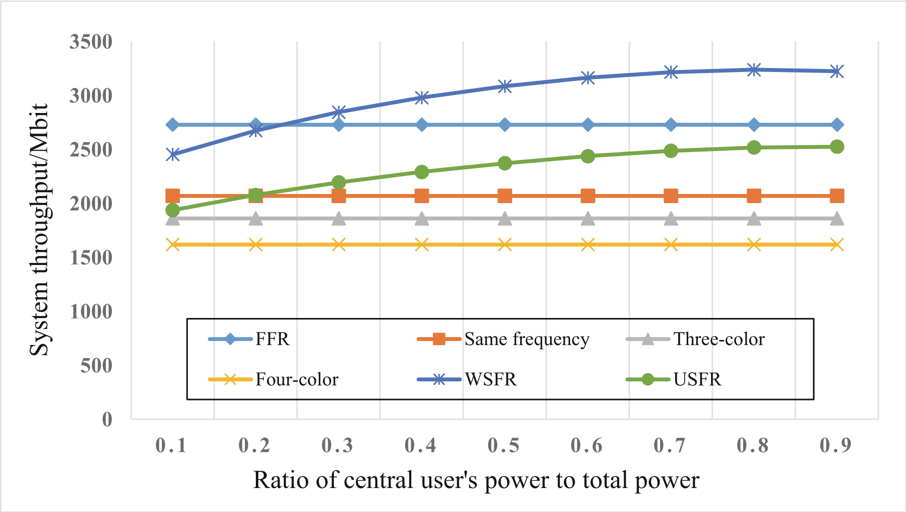

Fig. 4. Comparison of system throughput under different power ratios.

beam compared to USFR. When R_{center} is 30KM, the throughput performance of WSFR reaches 1.9 times that of four-color.

The system throughput under different power ratios is shown in Fig. 4. Power ratios refer to the ratio of power in the center area of the beam to the total power of the system. Since the power ratio only affects the performance of USFR and WSFR, the performance of other algorithms is horizontally straight. As the power ratio gradually increases, the throughput performance of USFR and WSFR gradually increases. This is because users in the center area have a better channel state, so the more resources the center user is allocated, the better the performance of the system. At the same time, the performance of WSFR is better than that of USFR at various power ratios. When the power ratio is 0.8, the throughput of the WSFR reaches twice that of the four-color.

To further illustrate that the hybrid architecture we propose can improve the performance of the system, we compared the satellite-aided cell-free system proposed in this paper with the traditional cell-free system, and the result is shown in Fig. 5. The terrestrial cell-free system in the figure refers to the throughput of the remaining terrestrial users after using the user selection algorithm proposed in this article. The satellite-aided cell-free system in the figure represents the total throughput of both terrestrial and satellite users. In this simulation, the number of APs in each beam is fixed in the three contrast scenarios.

Under different numbers of users, the performance of the hybrid architecture we propose is better than that of the traditional cell-free system. The performance of terrestrial users is also better than that of traditional cell-free system, which shows that the user selection algorithm we propose can effectively reduce the interference between systems, thereby improving the performance of the system.

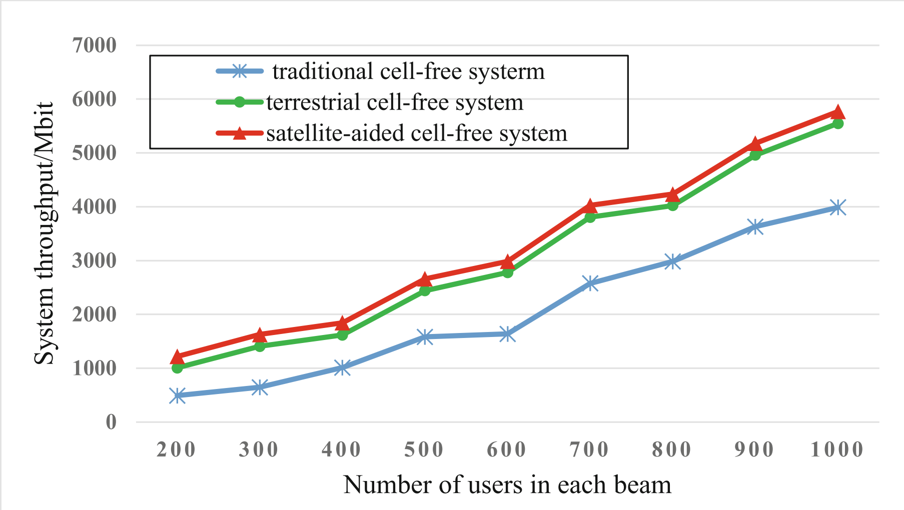

Fig. 5. Performance comparison of satellite-aided cell-free system and traditional cell-free system.

6 Conclusion

This paper proposes a hybrid communication framework that combines the benefits provided by cell-free massive MIMO with the large coverage of satellites. System models for the terrestrial and satellite segments are given separately. The simulation results show that the proposed user selection algorithm and resource allocation algorithm can reduce interference within the system and improve the throughput performance of the system.

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