Resource Allocation Mechanism for Cooperative Multicast in Integrated Satellite-Terrestrial Network

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***Abstract*—This paper develops a resource allocation mechanism of cooperative multicast under the integrated satellite-terrestrial network (ISTN). In cooperative multicast, base stations (BS) form different single frequency networks (SFN), and BSs within each SFN transmit data to mobile users (MU) with the same frequency, thus increasing signal intensity. Under this system architecture, we leverage the bottleneck user problem to characterize the overall system performance, where the bottleneck user is the MU with the lowest data rate inside each SFN. As the bottleneck user has poor signal strength, an SFN suffers a decrease in its Quality of Experience (QoE) provided to all users. Such an issue is alleviated under the ISTN: Users with poor signal strength can connect to the satellite that transmits with a moderate data rate, while the other users in the terrestrial network are unleashed from being grouped with them. In this regard, we propose an SFN-partitioning mechanism with the user-satellite association. In particular, our algorithm employs concepts from cooperative game theory and ensures Nash stability of the system. Finally, the simulation results validate the efficiency of the proposed mechanism.**

I. Introduction

Recent years have witnessed a surge in wireless connectivity demand with the prediction of over 300 EB mobile data traffic per month in 2027 [1]. To tackle this issue, researchers propose cooperative multicast to achieve better system performance without occupying additional frequency bands. Cooperative multicast groups base stations (BS) into single frequency networks (SFN), and within each SFN, all the BSs transmit data to the mobile users (MU) with the same frequency simultaneously, thus intensifying the signal inside each SFN [2]. Nevertheless, despite the above advantage, cooperative multicast suffers a major drawback. In multicasting, the modulation and coding scheme (MCS) of an SFN is devised based on the user with the lowest signal-to-interference-plus-noise ratio (SINR). Therefore, the MU with the lowest SINR becomes the bottleneck user that hinders the system performance. Also, users with good signal intensity suffer from being grouped with users with poor signal strength. Therefore, it is infeasible to group all the users into a single SFN. In this regard, the partitioning of BSs into different SFNs is a critical issue.

For 5G networks, SFN partitioning is the norm [3], [4]. Liu and Wei transform the system into a graph and devise a centralized graph-based greedy partitioning algorithm (GGPA) to optimize the sum log rate [3]. In [4], a dynamic MBSFN area formation (DMAF) algorithm is presented to maximize the aggregate data rate. Moreover, the authors leverage scalable video coding (SVC) to offer different service levels. Furthermore, with the envision of 6G, SFN partitioning is also considered for the non-terrestrial network [5]. However, although the above mechanisms utilize SFN partitioning to boost system performance, they still suffer from the bottleneck user problem.

On the other hand, with the emergence of satellite technology, the integrated satellite-terrestrial network (ISTN) is a promising system architecture. Some previous works have researched the incorporation of terrestrial and non-terrestrial communications [6]–[12]. A comprehensive survey of ISTN is given in [6], including resource allocation, mobility management, access control, security, etc. In [7], the authors utilize a convex approximation method to optimize cooperative multicast with the aid of a satellite. In [8], the unicast and multicast scenarios are both considered under the integration of the terrestrial network and the satellite. In [9], Shahid *et al.* propose methods to balance the load between terrestrial and non-terrestrial networks. The work in [10] jointly considers the cache placement and transmission scheduling in the ISTN. In [11], a spectrum sharing scheme between non-terrestrial network (NTN) and terrestrial network (TN) is proposed. In [12], the authors adopt a machine learning scheme to manage network resources in the ISTN. However, while the above work considers the integration of BSs and the satellite, they fail to take cooperative multicast into account.

Recently, Dai *et al.* explore the user association in the ISTN through a distributed user association with grouping (DUAG) mechanism [13]. Nevertheless, their work focuses on the grouping of users instead of SFN partitioning, but it is more desirable to examine cooperative multicast from a BS standpoint as BSs have more computational resources. Unlike the previous works, we jointly consider the SFN partitioning and the user-satellite association. Moreover, we leverage the concepts from cooperative game theory to characterize the SFN coalition formation between different BSs, and the resulting outcome achieves Nash stability. We summarize the contributions of the paper as follows.

1) We optimize the system performance of BSs and MUs through a system model of cooperative multicast under ISTN.
2) We tackle the bottleneck user problem with a resource allocation mechanism jointly considering SFN partitioning and user-satellite association.
3) The devised mechanism leverages cooperative game the-

ory to characterize the SFN coalition formation between different BSs and the satellite.

II. System Model and Resource Allocation Problem

In this section, we describe the system model (§II-A) and the resource allocation problem of cooperative multicast (§II-B).

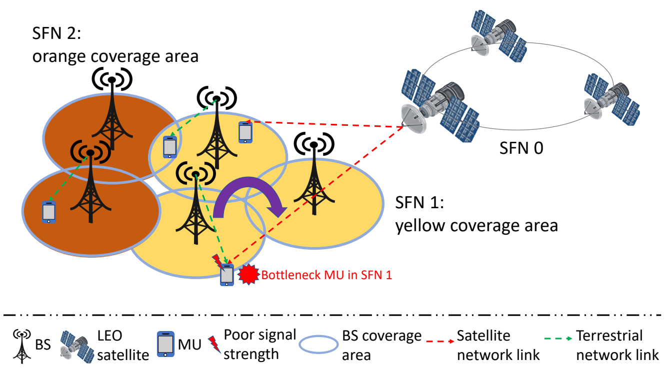


Fig. 1. An example of the network model in our scenario. SFN 0 consists of the satellite. SFN 1 and SFN 2 consist of BSs.

A. System Model

We consider a network system with a content provider (CP), a network service provider (NSP), several multi-antenna LEO satellites, P BSs, and Q MUs. LEO satellites, BSs, and MUs in the system model are shown in Fig. 1. To provide services to a target area for a certain period, satellites have coverage that does not overlap. Thus, we only need to consider a system with one satellite and P BSs, which are also referred to as access nodes (AN). ANs are expressed as $\mathcal{P} \triangleq \{p_0, p_1, ..., p_P\}$, where p_0 indicates the satellite. For the NSP, all BSs are connected to the CP via high-speed backhaul links, whereas the satellite acquires data from the CP through wireless transmission.

The set of all MUs is denoted by $\mathcal{Q} \triangleq \{q_1, q_2, ..., q_Q\}$. An MU downloads the content from either the BSs within transmission range or the satellite. We denote the relationship between ANs and MUs by $\mathbf{X} \triangleq (x_{pq} \in \{0, 1\} : p \in \mathcal{P}, q \in \mathcal{Q})$, where $x_{pq} = 1$ iff MU q connects to AN p. MUs acquire services from M SFNs, in which several ANs send the same content over the same frequency channel simultaneously. BSs coordinate with each other to form SFNs so that the signal strength increases due to constructive interference [2]. Let $\mathcal{M} \triangleq \{m_0, m_1, ..., m_{M-1}\}$ be the set of SFNs, where m_0 represents the SFN composed of the satellite, and the other SFNs consist of BSs. We denote the relationship between SFNs and ANs by $\mathbf{W} \triangleq (w_{mp} \in \{0, 1\} : m \in \mathcal{M}, p \in \mathcal{P})$, where $w_{mp} = 1$ iff AN p belongs to SFN m. Also, we denote N_m as the number of MUs served by all ANs in SFN m. Note that an AN is allowed to join a single SFN, and $w_{00} = 1$ because the long delay of the satellite-terrestrial link prevents the satellite from coordinating with BSs. An SFN can only send a content through multicast. Furthermore, all SFNs transmit contents synchronously.

To illustrate, Fig. 1 is an example with a satellite, $P = 5$ BSs, $Q = 4$ MUs, and $M = 2$ SFNs. SFN 0 is the satellite, and SFN 1 and SFN 2 are composed of three and two BSs, respectively. Although three SFNs transmit the same content synchronously, the frequency channels of each SFN may provide services with dissimilar quality to an MU. In SFN 1, MUs receiving good signal strength continue connecting to the BSs in SFN 1, whereas those receiving poor signal strength are assigned to other SFNs to acquire better service, such as the satellite in SFN 0.

B. Resource Allocation Problem

In this work, we aim to solve the bottleneck user problem, which is common in most SFN systems. A bottleneck user is defined as the MU that receives the lowest SINR in an SFN. Consider SFN 1 in Fig. 1. The MU whose location is almost outside the coverage area receives the poorest SINR compared with other MUs in SFN 1. This MU is the bottleneck user that represents the channel quality of the whole SFN.

Our goal is to maximize the summation of each SFN's Quality of Experience (QoE) score, which is the product of the QoE score of the bottleneck user and the number of users inside the SFN. The QoE score suitably reflects the influence of the bottleneck user in multicast and the user number in the communication system. In this work, we use Shannon capacity as the QoE score, but other metrics can also be adopted. Before the formal definition of the QoE score, we define the SINR received by MU q in SFN m as follows.

$$SINR_{mq} = \frac{TP \cdot \sum_{i \in \mathcal{P}} \{A_{iq} \cdot w_{mi}\}}{NP + TP \cdot \sum_{i \in \mathcal{P}} \{A_{iq} \cdot \neg w_{mi}\}}, \tag{1}$$

where A_{iq} is the signal attenuation transmitting from AN i to MU q, TP stands for the transmission power of an AN, and NP represents the power of noise. Both pathloss and shadowing are considered factors that influence the signal attenuation A_{iq}.

We denote the set of MUs belonging to SFN m as S_m. The minimum Shannon capacity for MUs connecting to SFN m is:

$$K_m = \min_{q \in S_m} B \log_2(1 + SINR_{mq}), \tag{2}$$

where B is the bandwidth provided by SFN m to MU q, and $SINR_{mq}$ denotes the SINR measured at MU q.

Several constraints should be satisfied.

$$w_{mp} \in \{0, 1\}, \forall m \in \mathcal{M}, p \in \mathcal{P}, \tag{3a}$$

$$x_{pq} \in \{0, 1\}, \forall p \in \mathcal{P}, q \in \mathcal{Q}, \tag{3b}$$

$$\sum_{m \in \mathcal{M}} w_{mp} = 1, \forall p \in \mathcal{P}, \tag{3c}$$

$$\sum_{p \in \mathcal{P}} x_{pq} = 1, \forall q \in \mathcal{Q}, \tag{3d}$$

$$\sum_{q \in \mathcal{Q}} \sum_{p \in \mathcal{P}} \sum_{m \in \mathcal{M}} w_{mp} x_{pq} \geq 1. \tag{3e}$$

The network model has defined the relationship between SFNs, ANs, MUs, and contents, which is denoted by Eq. (3a) and Eq. (3b). The constraints that every AN and every MU belongs to a single SFN are expressed as Eq. (3c) and Eq. (3d), respectively. Lastly, Eq. (3e) guarantees an MU q is served by an AN p in SFN m.

Using the minimum Shannon capacity in Eq. (2) as the QoE model, we have the following objective function.

$$\begin{aligned} J_d &= \sum_{m\in\mathcal{M}} K_m \cdot N_m \\ &= \sum_{m\in\mathcal{M}} \min_{q\in S_m} B\log_2(1+SINR_{mq}) \cdot N_m. \end{aligned} \tag{4}$$

The optimization goal J_d is the summation of the score of every SFN for content d transmission, which is calculated by multiplying the poorest QoE in the SFN by the number of MUs served. To solve the optimization problem, the constraints defined from Eq. (3a) to Eq. (3e) should be satisfied. Thus, the optimization problem is as follows.

$$\begin{aligned} &\max_{(\mathbf{W},\mathbf{X})} \sum_{m\in\mathcal{M}} \min_{q\in S_m} B\log_2(1+SINR_{mq}) \cdot N_m, \\ &\text{subject to } (1), (3a) - (3e). \end{aligned} \tag{5}$$

We use two methods to tackle Eq. (5). First, how we group ANs into SFNs affects the system performance. All ANs in the same SFN are restricted to sending identical content in a time slot. Finding a better permutation for the members of an SFN contributes to the QoE score. Second, MUs receiving poor signals are assigned to a new SFN. For instance, an MU located at the edge of the coverage area of BSs has low capacity. Assigning such kinds of MUs to the satellite improves the capacity of these receivers and increases the bottleneck QoE score of the original SFNs these receivers belong to. SFN assignment is thus influential to the optimization goal.

III. Mechanism Design and Theoretical Analysis

In this section, we propose a two-stage mechanism to solve the optimization problem. First, we utilize cooperative game theory to determine the SFN partitions among ANs (§III-A). Second, we employ SFN assignment to further improve the system performance by switching the belonging SFNs of some MUs (§III-B). Then, we give the theoretical analysis of the two-stage mechanism (§III-C).

A. SFN Partitioning

Since Eq. (2) is non-linear, and the decision variables are integers (Eq. (3a) and Eq. (3b)), the optimization problem in Eq. (5) is an integer nonlinear programming, which is NP-hard. Therefore, it is infeasible to find a solution efficiently. Instead, we use cooperative game theory with the transferable utility to solve the resource allocation problem. A coalition formation game is adopted to model our system. In particular, we define a coalition as an SFN. BSs and the satellite form coalitions to decide the system structure. We have the following definitions.

Definition 1 (Coalition). *A coalition $C_i \subseteq \mathcal{P}$ is a group of ANs in the same SFN i. The collection of coalitions can be expressed as $C = \{C_0, C_1, ..., C_{M-1}\}$, where C_0 represents the SFN for thr satellite, and C_i, $i \neq 0$, is composed of BSs. Note that all coalitions can be considered to be disjoint sets that span all players in $\mathcal{P}$, which indicates that $C_i \cap C_j = \emptyset, \forall i \neq j$, and $\bigcup_{i=0}^{M-1} C_i = \mathcal{P}$.*

Definition 2 (Utility). *A utility function $U(C_i)$ indicates the acquired total utility of coalition C_i. We aim to enhance the QoE for all MUs, so $U(C_i)$ is based on Eq. (2), which is defined as $U(C_i) = K_i \cdot N_i$.*

According to the above definitions, this is a coalition formation game with transferable utility, and the game formulation can be examined from the following perspectives:

1) *Players:* ANs in $\mathcal{P}$, including the satellite and BSs, are players in the grand coalition $\mathcal{P}$.
2) *Coalition Partition:* $C = \{C_0, C_1, ..., C_{M-1}\}$ is a collection of mutually disjoint coalitions that span $\mathcal{P}$.
3) *Strategy:* A player is allowed to join or leave a coalition except for the satellite.

When ANs collaborate as coalitions to boost the total QoE for MUs, we need to define a comparison relation for ANs to choose a proper coalition to join.

Definition 3 (Comparison Relation). *Given two coalition partitions C and C', we define a comparison relation $C' \triangleright C$, where partitions C' are preferred over partitions C. The comparison relation is as follows:*

$$C' \triangleright C \iff \sum_{i\in\mathcal{M}} U(C_i') > \sum_{j\in\mathcal{M}'} U(C_j). \tag{6}$$

The comparison relation is based on the total utility of all coalitions. A player switches from the original coalition C_i to the new coalition $C_{i'}$ iff the new summation of the utility of every coalition is larger than the original one. In other words, new coalition partitions C' form as players organize themselves into a preferred coalition so that the social welfare of the grand coalition is increased.

Next, we use the merge and split algorithm to model coalition formations. The algorithm consists of two operations.

1) *Merge Rule:* Any set of coalitions $\{S_1, ..., S_k\}$ can be merged whenever the merged form is preferred by players, where $\{\bigcup_{i=1}^{k} S_i\} \triangleright \{S_1, ..., S_k\}$; therefore, $\{S_1, ..., S_k\} \rightarrow \{\bigcup_{i=1}^{k} S_i\}$.
2) *Split Rule:* Any set of coalitions $\{\bigcup_{i=1}^{k} S_i\}$ can be split whenever the split form is preferred by players, where $\{S_1, ..., S_k\} \triangleright \{\bigcup_{i=1}^{k} S_i\}$; therefore, $\{\bigcup_{i=1}^{k} S_i\} \rightarrow \{S_1, ..., S_k\}$.

The coalition formation algorithm is presented in Alg. 1. First, an initial partition $C = \{C_0, C_1, ..., C_{M-1}\}$ is formed (line 1). Next, we repeatedly perform the merge rule and the split rule so that new coalition partitions with better system performance are selected. Note that we do not check C_0 because the coalition reserved for the satellite is not permitted to split or merge with BSs. In the stage of "Merge", the original coalitions are traversed in a predetermined order (line 3). Each coalition C_i attempts to merge with another coalition C_j except

Algorithm 1 Merge and Split Algorithm

1: Initialization: Random network partition $C = \{C_0, C_1, ..., C_{M-1}\}$
2: **while** C is not Nash-stable **do**
   Merge:
3:   **for** $i = 1$ to $M-1$ **do**
4:     **for** $j = 1, ..., i-1, i+1, ..., M-1$ **do**
5:       **if** $\{C_i \cup C_j\} \triangleright \{C_i, C_j\}$ **then**
6:         $C_i \leftarrow \{C_i \cup C_j\}$
   Split:
7:   **for** $i = 1$ to $M-1$ **do**
8:     $l = |C_i|$
9:     **if** $l > 1$ **then**
10:       $Per_i \leftarrow$ all possible permutations for splitting C_i
11:       **for** each Per_{ij} in Per_i **do**
12:         **if** $Per_{ij} \triangleright C_i$ **then**
13:           $C_i \leftarrow Per_{ij}$
14: **return** C

itself (line 4). Once the comparison relation in Eq. (6) is achieved, we merge C_i and C_j (line 5, 6).

Following the termination of "Merge", the algorithm enters the stage of "Split". Similar to "Merge", a coalition is selected one by one (line 7), and only coalitions consisting of over one AN can be split (line 9). The set of all possible split partition for C_i is denoted by Per_i. If any split partition satisfies the comparison relation, C_i will be split (line 12, 13).

The two-stage process is repeated until C is Nash-stable.

B. SFN Assignment

After the ANs belonging to each SFN are defined, we can further improve the solution to the optimization problem by assigning MUs to new SFNs. Some MUs suffer from low QoE scores in the original SFN, so we assign these MUs to a new SFN with higher SINR. The significant advantage of the satellite is identified in this stage. The MUs far away from nearby BSs often become the bottleneck users that compromise the whole SFN performance. If these MUs are transferred to SFN 0, the satellite can increase the SINR received by them. Unlike BSs faced with distance limitations, the satellite is crucial in enhancing the system performance.

To realize SFN assignment for MUs, we define a transfer condition to determine whether a MU should join a new SFN.

Definition 4 (Transfer Condition)**.** *For an MU q , we define a transfer condition $M_i \overset{q}{\succcurlyeq} M_j$, where SFN j is a better choice than SFN i for MU q. M_i' and M_j' are SFNs after MU q leaves original SFN i to join SFN j, a situation that improves the optimization goal. The transfer condition is as follows:*

$$M_i \overset{q}{\succcurlyeq} M_j \iff (K_i + K_j) < (K_i' + K_j'). \tag{7}$$

The SFN assignment algorithm is presented in Alg. 2. Bottleneck users are selected during initialization (line 1). Then, we repeatedly check whether assigning these bottleneck MUs to other SFNs can increase the system performance. If the transfer condition in Eq. (7) is satisfied (line 6), the MU will leave the old SFN and switch to the new SFN. The AN that provides the best network service in the new SFN connects with the MU, where p and p' denote respectively the original AN and new AN for the MU (line 7). After the completion of the transfer, the bottleneck users of SFNs are updated (line 7). Such a process is repeated until the QoE score cannot be enhanced by assigning any MU to other SFNs.

Algorithm 2 SFN Assignment

1: Initialization: Select the bottleneck user for each SFN $\mathcal{B} = \{b_0, b_1, ..., b_{M-1}\}$
2: **while** not Nash-stable **do**
3:   **for** $i = 0$ to $M-1$ **do**
4:     $q \leftarrow b_i$
5:     **for** $j = 0, ..., i-1, i+1, ..., M-1$ **do**
6:       **if** $M_i \overset{q}{\succcurlyeq} M_j$ **then**
7:         $p' \leftarrow \arg\max_{p'\ s.t. w_{jp'}=1} \quad SINR_{pq}$
8:         $x_{p'q} \leftarrow 1$, $x_{pq} \leftarrow 0$, and update b_i and b_j
9: **return** $\mathcal{X}$

C. Theoretical Analysis

In this subsection, we provide some theoretical analysis of the proposed two-stage mechanism. In particular, we prove that the mechanism converges to a Nash-stable SFN structure.

Theorem 1 (Convergence)**.** *The proposed two-stage mechanism converges to a valid SFN structure.*

Proof. Because the number of ANs and MUs is finite, the number of possible SFN structures is finite. Thus, the number of iterations is bounded when each iteration strictly increases the objective function. After a finite number of iterations, the two-stage mechanism terminates. Moreover, as the initial SFN structure is valid, and each iteration maintains the validity of SFN structures, the final SFN structure is also valid. □

Theorem 2 (Stability)**.** *The final SFN structure of the proposed two-stage mechanism is a Nash-stable solution.*

Proof. The proposed two-stage mechanism terminates when a successful SFN assignment no longer occurs. If the final SFN structure C is not Nash-stable, i.e., there exists coalition partitions C' such that $C' \triangleright C$, then SFN assignment will occur, and another SFN structure will form. Hence, C is not the final SFN structure, contradicting the claim that the mechanism has terminated. Thus, the final SFN structure of the proposed two-stage mechanism is a Nash-stable solution. □

IV. Numerical Simulation Results

In this section, the experimental setting and the evaluation of the simulation results are presented.

A. Experimental Setting

We consider an ISTN consisting of one LEO satellite and a 19-cell cellular network ($P = 19$). The parameters are listed in Table 1. We consult [14] for satellite transmission and [15] for BS transmission. As for the path loss model for the LEO satellite, we consider non-line-of-sight (NLOS) signal conditions in an urban scenario. For terrestrial communication channels, the path loss is modeled by $PL = 20\log(40\pi d f_c/3) + \min(0.03h^{1.72}, 10)\log d - \min(0.044h^{1.72}, 14.77) + 0.002d\log h$, where h is the average height of buildings, f_c is the carrier center frequency, and d is the distance between an MU and a BS in 3D space. Finally, the setting for inter-site distance (ISD) is referred from [16].

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of BSs	19
BS transmission power	43 dBm
BS antenna gain	8 dBi
Satellite transmission power	33 dBm
Satellite antenna gain	25 dBi
Noise power	−103 dBm
ISD	15 km
Average height of buildings h	5 m
Carrier center frequency f_c	2 GHz
Bandwidth	10 MHz

To evaluate the performance of our proposed mechanism, we compare it with the following mechanisms:

1) *All SFN (ASFN):* All cells are in a single SFN, which occupies the whole bandwidth of the system. Inter-bearer interference does not take place in this mechanism.
2) *All PTM (APTM):* Adjacent cells belong to different SFNs, and the total bandwidth is divided for different frequency channels with the frequency reuse factor $N_f = 3$. Inter-bearer interference occurs between adjacent cells.
3) *Graph-based Greedy Partitioning Algorithm (GGPA) [3]:* GGPA is a graph-based partitioning mechanism that consumes lower computation costs than exhaustive search while achieving good resource efficiency.

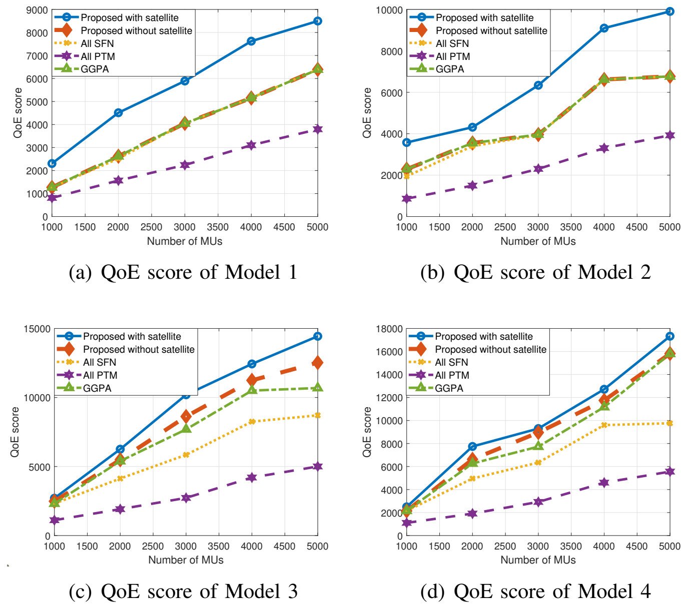
Note that the total bandwidth utilized by each mechanism is identical. In our mechanism, the total bandwidth is divided into two portions for the LEO satellite and the terrestrial network.

Our simulation considers 4 MU distribution models with different MU densities and location distributions, as summarized in Tbl. II.

1) *Model* 1*:* The number of MUs in every cell is the same, and the distribution of MUs in a cell is uniform.
2) *Model* 2*:* There are different numbers of MUs in each cell, and the distribution of MUs in a cell is uniform.
3) *Model* 3*:* Similar to Model 1, each cell contains an equal number of MUs. However, the distribution of MUs is clustered. The radius of the cluster is 1.875 km.
4) *Model* 4*:* Similar to Model 2, the MU density is dissimilar. However, the distribution of MUs is clustered.

TABLE II
FOUR MU DISTRIBUTION MODELS

Distribution model	MU density	MU location distribution
Model 1	fixed	uniform
Model 2	varying	uniform
Model 3	fixed	clustered
Model 4	varying	clustered



(a) QoE score of Model 1 (b) QoE score of Model 2

(c) QoE score of Model 3 (d) QoE score of Model 4

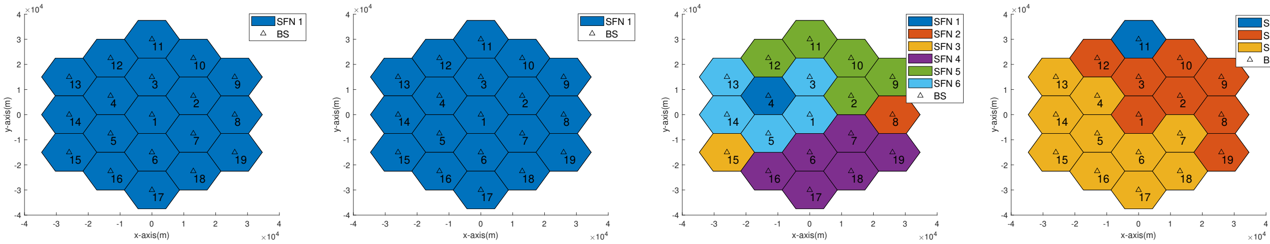
Fig. 2. Simulation results for 4 models. The blue line is our complete mechanism with the satellite: SFN partitioning + SFN assignment, and the orange line is our mechanism without the satellite: SFN partitioning only.

B. Performance Evaluation

The performance of the considered mechanisms for different models is evaluated with the proposed QoE metric in Eq. (5) (normalized by total bandwidth). According to different total numbers of MUs in the system, the performance evaluation for five mechanisms is shown in Fig. 2.

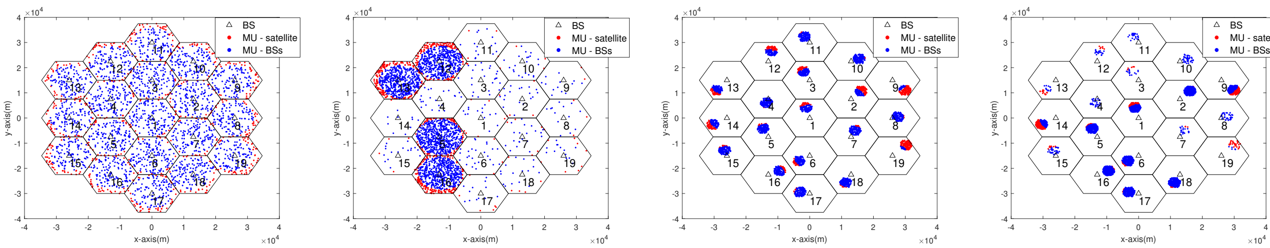
First of all, we evaluate the performance of the first stage of our mechanism of SFN partitioning in Fig. 2, which utilizes cooperative game theory without taking advantage of satellite transmission. Our SFN-partitioning mechanism outperforms the other methods. Note that our mechanism has similar performance compared with GGPA in all scenarios. Based on the experimental results in [3], GGPA has achieved a performance whose value is over 95% of the value of the optimal solution. Hence, the similarity of performance between our mechanism and GGPA indicates the quality of our solution.

Compared with ASFN and APTM, our mechanism demonstrates observable superiority in QoE scores. The proposed mechanism is slightly better than ASFN when the MU distribution is uniform (Model 1 and 2) but outperforms it significantly in clustered distribution (Model 3 and 4). When the scattering of MUs is uniform, the QoE scores of the bottleneck user in all cells do not vary considerably. Therefore, ASFN becomes a suitable solution that provides high-quality services to MUs in Model 1 and 2. By contrast, the clustered distribution in Model 3 and 4 leads to the dissimilarity in the minimum capacity of all cells, thereby compromising the performance of ASFN. As for APTM, the performance is the worst since the signals from adjacent cells belonging to different SFNs become interference. Conversely, ASFN and other mechanisms allow neighboring cells to form an SFN so that signals from multiple transmitters lead to a higher SINR.



(a) SFN partitioning of Model 1 (b) SFN partitioning of Model 2 (c) SFN partitioning of Model 3 (d) SFN partitioning of Model 4

Fig. 3. An example of SFN partitioning for 4 models when there are 3000 MUs. Each colored area is an SFN. Digits in the figure are used to indicate the index of the cell.



(a) Connection of Model 1 (b) Connection of Model 2 (c) Connection of Model 3 (d) Connection of Model 4

Fig. 4. An example of user association for 4 models when there are 3000 MUs. The blue points are MUs that connect to the terrestrial network, and the red points are MUs that connect to the satellite. Digits in the figure are used to indicate the index of the cell.

We now observe the performance improvement of our complete two-stage mechanism in Fig. 2, including SFN partitioning and SFN assignment. SFN assignment is conducive to increasing the QoE score. MUs encountering poor network services from BSs are assigned to the satellite or other SFNs. This strategy not only boosts the Shannon capacity of the MU but enables the bottleneck capacity in the original SFN to increase. Then, SFN partitioning is re-calculated to achieve a better performance. Repetition of such a process until reaching Nash stability enables our mechanism to yield marked improvement compared with mere SFN partitioning. In addition, the improvement in Model 1 and 2 are more notable. For models with uniform MU distribution, MUs are more likely to be located at the border between adjoining cells. Such user distribution results in lower SINR for bottleneck users. Thus, our mechanism of transferring bottleneck MUs to the satellite has a more significant impact on Model 1 and 2.

C. Results of SFN Partitioning and SFN Assignment

To better understand the system characteristics, we examine the SFN partition and user association results of our two-stage mechanism. An example with 3000 MUs is considered. Fig. 3 presents the final SFN partitioning result, and Fig. 4 is the connection relationship between MUs and APs (BSs and the satellite).

For models with uniform MU distribution (Model 1 and 2), the final SFN partitioning in Fig. 3(a) and Fig. 3(b) is identical to the result of ASFN. Since the SINR distribution of neighboring cells does not vary much, ASFN can yield good performance. As for the MU connection relationship in Fig. 4(a) and Fig. 4(b), MUs on the edge of cells are more likely to be assigned to the satellite. These MUs are likely to have lower signal strength, so they tend to become bottleneck users. Thus, when our mechanism allows these MUs with lower SINR to connect to the satellite, the bottleneck capacity of the SFN increases.

Different from models with uniform MU distribution, the SFN structure is more complex for models with clustered distribution (Model 3 and 4). In Fig. 3(c) and Fig. 3(d), there are small SFNs composed of a single cell and medium-sized SFNs consisting of multiple cells. Small SFNs are more likely to form when MUs in the cell are very close to the BS, such as Cell 4, 8, and 15 of Model 3 in Fig. 4(c), and Cell 11 of Model 4 in Fig. 4(d), respectively. Our SFN partitioning mechanism lets this kind of cells form independent SFNs because the bottleneck capacity of the cell is already high. Conversely, if these cells combine with neighboring cells to become a new SFN, the users in the original SFN suffer from being grouped with users with poor SINR. Therefore, they tend to form small SFNs. For medium-sized SFNs, they consist of cells whose MUs cluster far away from the center. The formation of such SFNs depends on the clustered MU distribution.

Finally, we examine the MUs connecting to the satellite in Fig. 4(c) and Fig. 4(d). These MUs are more likely to be on the border of SFNs. For instance, we can look closer to SFN 6 of Model 3 in Fig. 3(c). MUs of Cell 1, 3, 13, and 14 in Fig. 4(c) are located at the edge of the SFN. By assigning MUs that receive poor signal strength to the satellite, our mechanism is able to improve the QoE score of the SFN.

V. Conclusion

In this paper, we consider cooperative multicast with the aid of a satellite. With cooperative multicast, BSs form SFNs to increase signal strength and the overall QoE score.

Furthermore, the satellite helps mitigate the bottleneck user problem, in which the user with the lowest SINR hampers the system performance. We formulate an optimization problem and propose a mechanism to tackle it. On the other hand, we leverage cooperative game theory in SFN formation to achieve system stability.

We conduct extensive simulations to demonstrate the superiority of the proposed mechanism compared with other benchmarks, and we have the following observations. When the MUs are uniformly distributed, all BSs tend to form a single SFN. Conversely, in clustered distribution, multiple SFNs are constructed. In this scenario, there are two kinds of SFN structures and user-satellite associations. First, when the MUs are close to the center of the cell, the BS will form a single SFN without coordinating with other BSs. Fewer MUs are assigned to the satellite because the QoE improvement is slight. By contrast, multiple BSs may cooperate to form an SFN. In this situation, the MUs will stay connected to the terrestrial network when located at the center of the SFN, even if they are far away from any particular BS. Furthermore, MUs staying on the border of SFNs tend to connect to the satellite.

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