Coalition among Multiple Providers of LEO Satellite Networks

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***Abstract*—In recent years, the low earth orbit (LEO) satellite network has attracted much attention. LEO satellites enable low latency communications, however the communication range of individual satellites is narrow, requiring a constellation of many satellites. The limited number of satellites in the initial phase of service provisioning limits the service area and communication time, making it difficult to secure users. In this paper, we propose a model in which multiple LEO satellite operators cooperate to provide services, and the revenue is reasonably allocated to each service provider based on the Shapley value of cooperative game theory. The possibility of extending communication services through cooperation among operators is verified through numerical evaluations.**

***Keywords*-LEO sateliite; satellite communication; cooperative game**

I. Introduction

In recent years, the space industry has experienced significant growth, and there is growing interest in broadband provided by LEO satellite networks with large satellite constellations [1] [2] [3]. Declining satellite launch costs and operation cost per capacity are the main factors [4]. The satellite communications network consists of satellites in LEO (Low Earth Orbit), MEO (Middle Earth Orbit) and GEO (Geostationary Orbit) orbits. It circles the Earth in about 90 to 120 minutes. MEO is a medium orbit of 2,000 km to 20,000 km above the Earth and can observe a wider area of the earth than LEO satellites. GEO is a geostationary orbit with an altitude of 36,000 km and can observe almost the same area of the earth because it moves at the same speed as the earth rotation. The orbits of LEO, MEO, and GEO are used for communication satellites and broadcasting satellites that relay radio communications and broadcasts, while MEO is used for positioning satellites that transmit signals necessary to measure positional information [5].

The use of LEO satellites, which have a low orbital plane, as communication satellites has the advantage of low latency due to their low orbit, however the range of coverage from the satellite is limited. SpaceX Starlink will begin Internet communications services in 2020,and as of January 2025, there are nearly 7,000 LEO satellites in operation [6]. However, the LEO satellite constellation does not perform well in the early stages of the project, e.g., several tens to several hundreds of satellites. This is because a small number of satellites cannot provide sufficient coverage of the Earth. Even if coverage is achieved, the available bandwidth is often too limited to deliver normal communication services. As a result, if the operator does not start service in the initial phase of the business, the revenue for that period will be zero, and even if the service is started, the revenue will be low [7]. In this study, we present a cooperative service model among LEO satellite operators, determine an appropriate distribution amount for participating operators in the initial phase, and demonstrate its effectiveness. To achieve this, satellites are shared among LEO satellite operators to form a satellite constellation, and a revenue-sharing method based on tie-up game theory is introduced. The effectiveness of this distribution method is validated through computer simulation.

II. Related Work

Huang et al. examined the effects of consumer adoption rate, inclination, and the number of orbital planes on customer growth when service providers share satellite capacity and showed that cooperation increases customer growth [8]. In particular, they investigated the benefits of sharing underutilized resources between two satellite groups for owners of small satellite groups who were more likely to pursue cooperation. However, they did not assume cooperation among real satellite operators and did not discuss revenue allocation.

Osoro et al. proposed an open-source modeling framework for evaluating the technical economics of satellite broadband connectivity and the impact on coverage, capacity, and cost as both the number of satellites and subscribers increased. They evaluated three major LEO satellite operators, Starlink, OneWeb, and Kuiper [9] and considered the initial phase of the business by varying the number of satellites, however did not mention revenues. Lian et al. proposed an evaluation method that took into account the actual needs of the ground users of the constellation and considered revenue and efficiency, and computer simulations showed that Starlink's constellation was less efficient than OneWeb's, however significantly more profitable [10]. They also showed that adjusting the structure of the

Starlink constellation improved the efficiency and profitability of the constellation. Although they considered revenue, they assumed that the satellites were well deployed.

Pachler et al. compared and analyzed the performance of four LEO satellite mega constellations of Telesat, OneWeb, SpaceX (Starlink), and Amazon in terms of throughput and satellite efficiency (average capacity utilization) in the initial phase and in the final phase [11]. The analysis was for the initial phase, however not for the revenue.

In this paper, we analyze the profitability of operators in the initial phase of satellite communications using LEO satellite constellations. As a solution to the low or no profitability in the initial phase, we propose that LEO satellite operators cooperate with each other and propose a revenue sharing method through a cooperative game game, which is numerically evaluated. By assuming cooperation from actual businesses, we analyze a more realistic situation.

III. Modeling Multiple Operators

A. Cooperative Games

Cooperative game theory is known as a theory that discusses how to form alliances in the presence of multiple autonomous players and how to distribute profits to each player [12]. In cooperative game theory, several solutions have been proposed for the distribution of profits among players, including cores, bargaining sets, kernels, nucleolus, Banzhaf values, and Shapley values. For example, Kimms and Cetiner proposed a nucleolus-based system that distributes profits to individual airlines participating in an airline alliance [13]. The core, bargaining set, and kernel are called the set of solutions, and no single solution can be obtained.

On the other hand, the nucleolus, Banzhaf value, and Shapley value are unique solutions based on different ideas. The nucleolus finds the most desirable solution in lexicographic order based on the excess, which is the difference between the benefit gained by the coalition and the sum of each player's allocation. In contrast, the Banzhaf and Shapley values are methods that calculate the average marginal contribution of each player. Banzhaf and Shapley differ in that Banzhaf assumes that coalitions are chosen with equal probability, while Shapley assumes that all sequences in the coalition formation order are chosen with equal probability. In this study, we use the Shapley value because it fairly evaluates the contributions of the players and makes the distribution clear.

B. Assumed Conditions

As for revenues, satellite communication services using LEO satellites are generally charged on a monthly basis. Therefore, this paper adopts a monthly fee model. However, since it is difficult to estimate an actual monthly fee, a fixed and uniform amount is assumed for all service providers, and numerical evaluations are conducted based on this assumed revenue. The communication range of the satellite is divided into grid cells by drawing a grid on the earth. Figure 1 shows the effect of cooperation between operators, where the black and blue circles represent satellites from different satellite operators. If a satellite is present in a grit cell, the subscribed users in that grit cell can communicate, on the other hand if multiple satellites are present in a grit cell, the bandwidth increases, resulting in faster per-user communication speeds and an increase in the number of users who can communicate. The number of satellites in a grid cell is called the coverage multiplicity, and communication between LEO satellites is assumed to be possible between all operators.

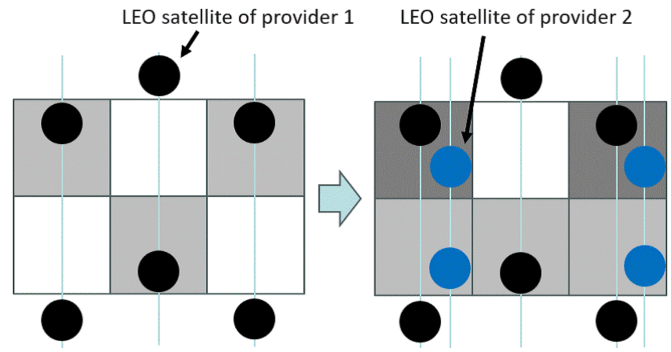

Fig. 1. Cooperation of operators

The scenario of cooperation among multiple service providers of LEO satellite networks would be as follows.

1. Operators cooperate by sharing satellites in the early deployment phase.
2. Coverage expands, and more satellites cover each area (higher multiplicity).
3. User satisfaction increases due to broader coverage and faster speeds.
4. More users subscribe, attracted by improved service quality.
5. Revenue grows as the number of subscribers increases.
6. Revenue is shared among operators based on their contributions.

C. Modeling

First, the communication range R_s of the LEO satellite is defined. Based on the viewing angle from the satellite to the horizon, R_s is obtained geometrically using the angle between the line connecting the center of the earth and the line tangent to the earth's surface in Equation (1),

$$R_s = R_e \cos^{-1}\left(\frac{R_e}{R_e + H}\right). \tag{1}$$

Let R_e be the radius of the earth, and H is the altitude of the satellite. If a satellite is in a grid cell, it can communicate within that cell. When multiple satellites are in a cell, coverage multiplexing is increased to provide more bandwidth to the user.

The actual grid cell areas near the poles and near the equator are very different, and the grid cells near the poles do not accurately represent the communication range of the satellite, however the polar regions are less populated and do not introduce significant errors in the computer simulation.

In cooperative game theory, the gain of the entire alliance is called the characteristic function v, so the characteristic function v in this paper is the profit of the entire alliance at the time of cooperation. Let $v(i, j)$ be the characteristic function for the alliance between satellite operators i and j. Where N denotes the set of all players participating in the game, and $N = \{i, j\}$, the Shapley value is obtained by the following Equation (2) for a 2-player game,

$$\phi_i(v) = v(i) + \frac{1}{2}\{v(i,j) - v(i) - v(j)\}, i = 1, 2. \quad (2)$$

The revenue $G_{i,k}$ of grid cell k of satellite operator i is obtained by Equation (3),

$$G_{i,k} = \alpha_{i,k}\beta. \quad (3)$$

Note that k is the number assigned to each cell after dividing the earth's surface into grid cells. $\alpha_{i.k}$ is the number of subscribers to grid cell k of satellite operator i, and β is the monthly fee per subscriber for LEO satellite communication services.

Defining S_i as the set of grid numbers covered by operator i, we obtain $v(i,j)$ from Equation (4),

$$\begin{aligned} v(i,j) &= \sum_{k\in S_{all}} G_{i+j,k} \\ &= \Bigg(\sum_{k\in S_i\cap S_j} \alpha_{i+j,k} + \\ &\quad \sum_{k\in S_i\cap \bar{S_j}} \alpha_{i,k} + \sum_{k\in \bar{S_i}\cap S_j} \alpha_{j,k}\Bigg)\beta. \end{aligned} \quad (4)$$

The number of subscribers $\alpha_{i,k}$ in grid cell k of satellite operator i is defined by the following Equation (5),

$$\alpha_{i,k} = \begin{cases} \sum_{c\in D_k} P_{k,c}C_{i,c}, & \text{if } \sum_{c\in D_k} \frac{\mu_{i,k}\gamma_i}{P_{k,c}C_{i,c}U} > 1, \\ \frac{\mu_{i,k}\gamma_i}{U}, & \text{if } \sum_{c\in D_k} \frac{\mu_{i,k}\gamma_i}{P_{k,c}C_{i,c}U} \leq 1, \end{cases} \quad (5)$$

where $P_{k,c}$ is the population of country c in grid cell k, D_k is the set of countries in grid cell k, $C_{i,c}$ is the subscription rate of satellite operator i in country c, U is the average traffic per person (bps), γ_i is the bandwidth of operator i's satellite bandwidth (bps).

Let $\mu_{i,k}\gamma_i$ be the supply communication volume in grid cell k and $P_{k,c}C_{i,c}U$ is the demand communication volume in grid cell k. If supply exceeds demand, everyone who wants to subscribe can do so, so the number of subscribers is the product of the grid cell population $P_{k,c}$ and the subscription rate $C_{i,c}$. However, if the demand is lower, the number of subscribers is the quotient of $\mu_{i,k}\gamma_i$ divided by U, since the number of subscribers may increase only up to the maximum number for which the service can be provided successfully. The population $P_{k,c}$ is obtained from the area and population density by the following Equation (6),

$$P_{k,c} = \lambda_{k,c}\eta_c, \quad (6)$$

where $\lambda_{k,c}$ is the area in country c grid cell k, and η_c is the population density in country c.

The contract rate $C_{i,c}$ assumes a logistic function (7),

$$C_{i,c} = \tau_i\left(C_{c,\min} + \frac{C_{c,\max} - C_{c,\min}}{1 + e^{-10(\epsilon_i - 0.5)}}\right). \quad (7)$$

However, τ_i is the per-operator coefficient based on the operator's evaluation. ϵ_i is the satisfaction level of satellite operator i in grid cell k. Since the upper and lower limits of the utilization rate, $C_{c,\max}$ and $C_{c,\min}$, are considered to be different in different countries, upper and lower limits are provided. In numerical evaluation, the upper and lower limits are determined based on the U.S. upper limit $C_{US,\max}$ and lower limit $C_{US,\min}$. This is because it is easy to determine the upper limit of the subscription rate based on the number of Starlink subscribers in the U.S. The upper and lower limits for each country correspond to the range of contract rates based on the internet penetration rate, which is determined by comparing it with country c internet penetration rate I_c. I_{US} is defined as the internet penetration rate in the U.S. The Internet penetration rate is based on data from the World Bank. The scale factor F_c for country c, the upper limit of the contract rate $C_{c,\max}$, and the lower limit $C_{c,\min}$ are calculated using Equations (8)(9)(10),

$$\begin{aligned} F_c &= \frac{I_c}{I_{US}}, & (8) \\ C_{c,\max} &= C_{US,\max}F_c. & (9) \\ C_{c,\min} &= C_{US,\min}F_c, & (10) \end{aligned}$$

We also define the satisfaction ϵ_i as a logarithmic function (11),

$$\epsilon_i = \log 1.5\{\rho\omega_i + (1-\rho)\mu_i\}, \quad (11)$$

where ω_i is the average coverage of satellite operator i, and $\omega_{i,k}$ is the average coverage of grid cell k of satellite operator i. ω_i is 1 if a satellite of satellite operator i exists in grid cell k and 0 otherwise. Also, μ_i is the average coverage multiplicity of satellite operator i, and μ_i, the coverage multiplicity of grid cell k of satellite operator i. μ_i is the number of satellites of satellite operator i in grid cell k. ρ is a weight and takes value in the range of $0.5 < \rho < 1$, because it is natural that an increase in coverage multiplicity contributes more to subscriber satisfaction than an increase in coverage multiplicity. This is because the increase in coverage (communication range) due to an increase in coverage ratio is more important to subscribers than the increase in bandwidth due to an increase in coverage multiplicity.

IV. Numerical Evaluation

A. Evaluation Conditions

Assuming that the earth radius R_e is approximately 6,371 km and the satellite altitude H is 550 km, the communication range diameter R_s is 2,557 km, as shown in Figure 2. This area is divided into square grid cells with a side of 1,809 km, which is the communication range. The entire earth is approximated to be 39,798 km in length and divided into 22×22 grid cells. For the area and population density of each country, we use Natural Earth in the python library and the World Bank's 2021 data [14].

Constellation *Conste1* is modeled after OneWeb and constellation *Conste2* is modeled after Qianfan. Conste1 has an altitude of 1,200 km, an inclination of 87.9 degrees, an orbit of 18, and a total number of satellites of 648. Conste2 has

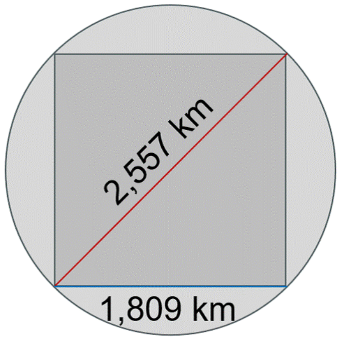

Fig. 2. Grid cell size

an altitude of 813 km, an inclination of 89 degrees, an orbital plane of 18, and a total number of satellites of 648.

Figures 3 and 4 show the coverage rate per grid cell $\omega_{c1,k}$ and the coverage multiplicity per grid cell $\mu_{c1,k}$. Since conste1 is a polar orbit constellation where the satellite passes near the north and south poles due to the inclination of 87.9 and near 90 degrees, neither the satellite coverage nor the coverage multiplicity varies significantly from grid to grid cell. The coverage multiplicity of conste1 does not vary significantly from grid cell to grid cell. The coverage of conste1 is denoted by $\omega_{c1,k}$, and the coverage multiplicity is denoted by $\mu_{c1,k}$. These averages are ω_{c1} and μ_{c1}.

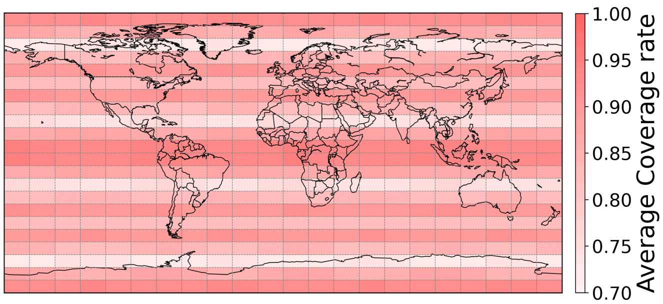

Fig. 3. Average coverage rate of conste1

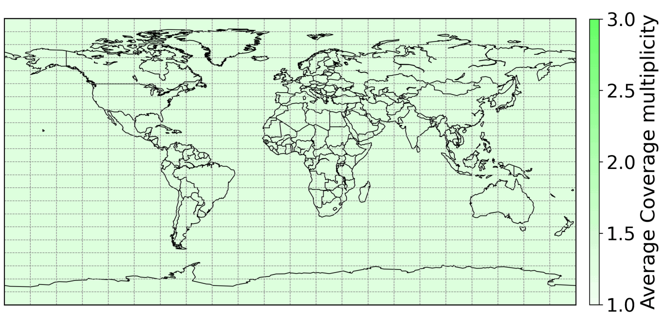

Fig. 4. Average coverage multiplicity of conste1

Figures 5 and 6 show the coverage rate $\omega_{c2,k}$ and coverage multiplicity $\mu_{c2,k}$ of conste2 for each grid cell. Since conste2 has an inclination angle of 89 degrees and is a polar orbit constellation like conste1, the satellite coverage rate and coverage multiplicity do not change significantly for each grid cell. The coverage rate of conste2 is $\omega_{c2,k}$, and the coverage multiplicity is $\mu_{c2,k}$. The averages are ω_{c2} and μ_{c2}.

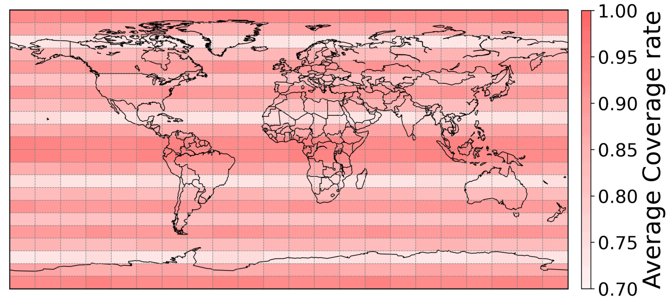

Fig. 5. Average coverage rate of conste2

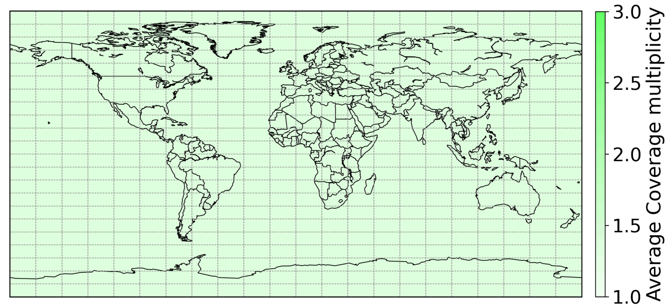

Fig. 6. Average coverage multiplicity of conste2

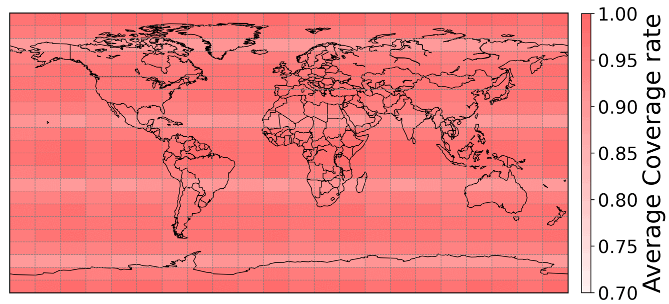

Fig. 7. Average coverage rate of conste1+2

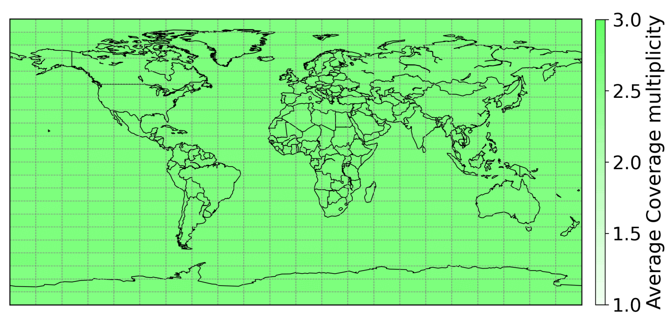

Fig. 8. Average coverage multiplicity of conste1+2

Figures 7 and 8 show the coverage rate $\omega_{c1+c2,k}$ and coverage multiplicity $\mu_{c1+c2,k}$ for each grid cell when conste1 and conste2 are combined to form one cooperative constellation. By cooperating, the coverage rate approaches 1, and the coverage multiplicity is the sum of the coverage multiplicities of conste1 and conste2. The coverage rate of the cooperative constellation is denoted by $\omega_{c1+c2,k}$, and the coverage multiplicity is denoted by $\mu_{c1+c2,k}$. The averages are ω_{c1+c2} and μ_{c1+c2}.

TABLE I
PARAMETER SETTINGS USED IN EVALUATION

Variable	Value
β	100 ($)
U	0.5 (Mbps)
γ	20,000 (Mbps)
$C_{\text{US,max}}$	0.01
$C_{\text{US,min}}$	0
ρ	0.8

Table I shows the parameter setting values needed to obtain the number of subscribers. The monthly fee, β, is based on the price of Starlink's individual use [15]. Also, C_{US_max} is based on the number of Starlink subscribers in the United States.

B. Effect of Cooperation Among Service Providers of LEO Satellite Networks

We assume three scenarios of 0.05, 0.5, and 5.0 for the average per capita traffic U when using satellite communications. Calculate the revenue for each and distribute using the Shapley value if it satisfies the superior additivity property. The value of $U = 0.5$ is assumed to be the amount of traffic that would be generated if all the average communication on a smartphone were done via satellite communication. The condition for satisfying superiority is that the revenue of the cooperative constellation must be greater than the sum of the revenue of const1 and const2. Super additivity is a necessary condition for the existence of a cooperative game.

The revenue of each operator when $U = 0.05$ and the total revenue of both operators at the time of the partnership are shown in Figure 9. The revenues are 994,664,495 for conste1 alone, 996,730,657 for conste2 alone, and 4,120,374,181 for the cooperative constellation. The revenue of the cooperative constellation is approximately 2.07 times the sum of the revenue of conste1 and conste2, which satisfies the Euclidean property. This is because the satellite coverage multiplicity μ causes a difference in the satisfaction level ϵ. Cooperation between operators with equal number of satellites increases the coverage multiplicity by about 2 times between conste1 and conste2, and the satisfaction level is about 0.6669 when they cooperate, compared to about 0.3530 for conste1 and 0.3533 for conste2. When the Shapley values are used to distribute the revenue, the distribution of revenue for each operator and the revenue when not cooperating are shown in Figure 10. Both conste1 and conste2 increase their earnings through cooperation, increasing their earnings by a factor of about 2.07.

When $U = 0.5$, the revenue is $506,255,176$ for conste1 alone, $506,694,898$ for conste2 alone, and $1,303,571,676$ for the cooperative constellation, as shown in Figure 11. The revenue of the cooperative constellation is $1,303,571,676$. The revenue of the cooperative constellation is approximately 1.29 times the sum of the revenue of conste1 and conste2, satisfying the eugenic law property. This is for the same reason as when $U = 0.05$. Also, as shown in Figure 12, when the Shapley value is used to distribute the earnings, the conste1 allocation, N1 Shapley, is $651,565,976$, and the conste2 allocation, N2 Shapley, is $652,005,699$. Both conste1 and conste2 increase their revenues through cooperation, and the rate of increase is approximately 1.29 times.

When $U = 5$, the revenues are $89,789,911$ for conste1 alone, $98,196,157$ for conste2 alone, and $196,370,240$ for the cooperative constellation, as shown in Figure 13. The revenue from the cooperative constellation will be $196,370,240$. The revenue of the cooperative constellation is approximately 1.09 times the sum of the revenue of conste1 and conste2, which satisfies the Euclidean property. This is for the same reason as when $U = 0.05$. Also, when the Shapley values are used to distribute the earnings, the conste1 allocation, N1 Shapley, is $98,174,082$ and the conste2 allocation, N2 Shapley, is

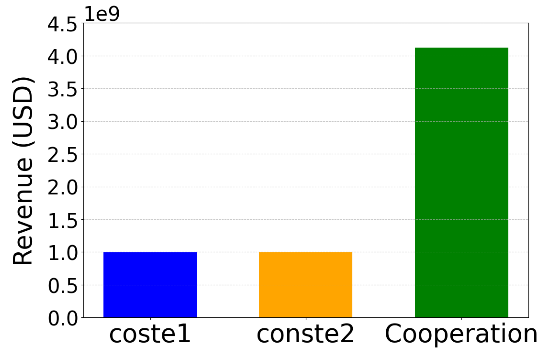

Fig. 9. Amount of revenue in three cases ($U = 0.05$)

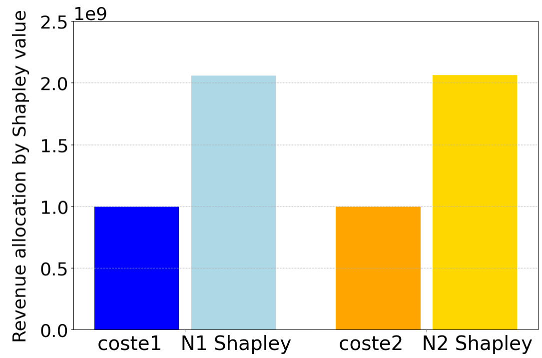

Fig. 10. Revenue allocation based on Shapley value ($U = 0.05$)

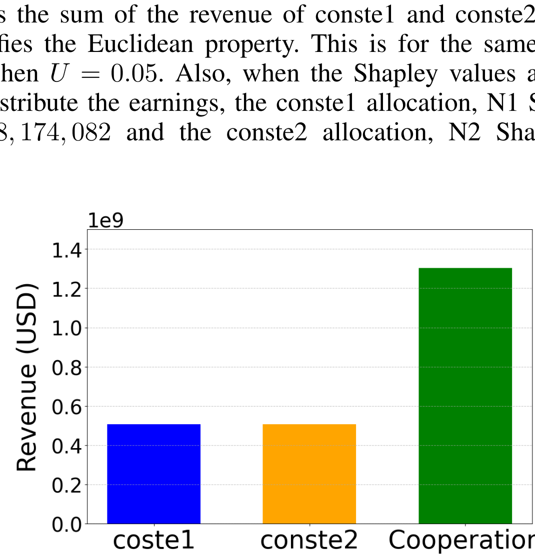

Fig. 11. Amount of revenue in three cases ($U = 0.5$)

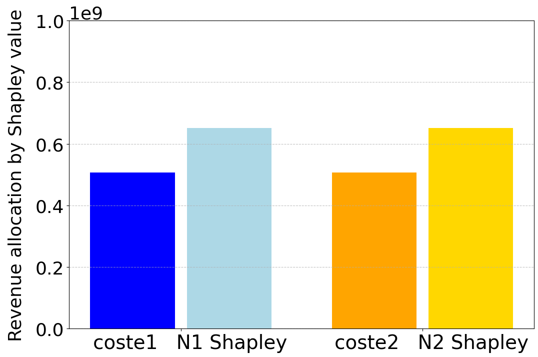

Fig. 12. Revenue allocation based on Shapley value ($U = 0.5$)

$98, 196, 157$, as shown in Figure 14. Both conste1 and conste2 increase their revenues through cooperation, with a revenue growth rate of approximately 1.09 times.

In all three scenarios, revenues increase, however the rate of increase in revenues is smaller for larger U. This is because when U is large, there are more grid cells where demand exceeds supply even in the absence of cooperation.

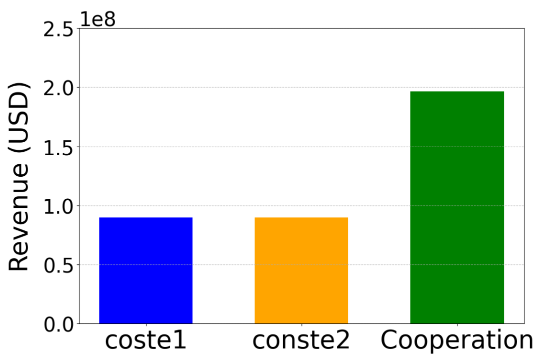

Fig. 13. Amount of revenue in three cases ($U = 5$)

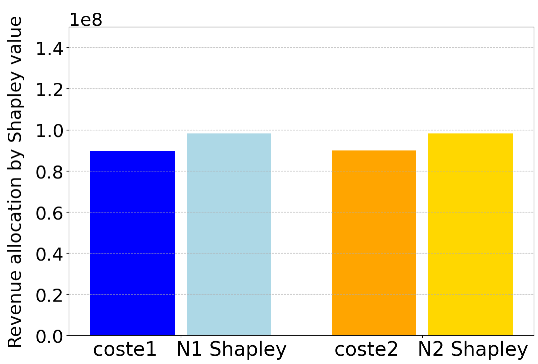

Fig. 14. Revenue allocation based on Shapley value ($U = 5$)

V. Conclusion

In this paper, we proposed a cooperation model among multiple service providers to address issues in telecommunication services utilizing LEO satellite networks, and we verified the effectiveness of the model through a tie-up game and computer simulations based on tie-up game theory. The proposed model enabled the sharing of satellites among service providers, and showed the possibility of increasing profits and expanding services through cooperation. The simulation results confirmed that the cooperation model satisfies eugenics in many cases and lead to increased revenues for each operator under multiple scenarios with different traffic volumes. In particular, the improvement of satellite coverage tended to increase the satisfaction with the telecommunication service and to increase the revenues.

In future work, we will first systematically derive the conditions for satisfying the eugenic property, thereby further clarifying the guidelines for applying the cooperative model. Furthermore, by extending the current two-party cooperation model and constructing and verifying a cooperation model among three or more operators, we aim to demonstrate the effectiveness of the model in a more complex business environment.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 23K21665, 23K21664, and 23K28078.

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