Coalition among Multiple Providers of LEO Satellite Networks

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Background

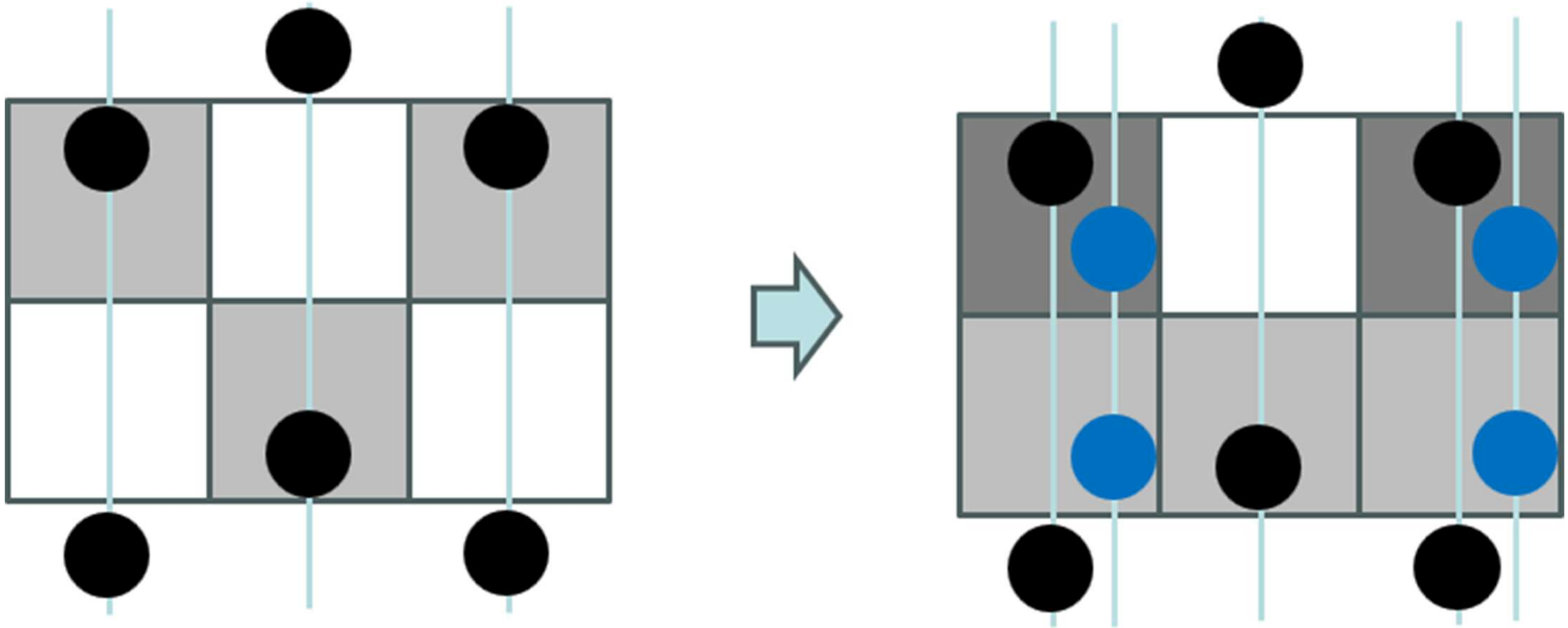
- LEO(Low Earth Orbit) satellite
  - Orbiting the Earth at altitudes up to 2,000 km, completing one revolution in approximately 90–120 minutes
  - Provides low-latency communication, though the coverage area on the ground is limited LEO
- LEO Satellite Communication Networks
  - Requires the construction of satellite constellations with many satellites to achieve global coverage

Overview

- Problem
  - LEO satellite constellations in the early stages cannot fully demonstrate their performance.
- Objective
  - Propose a cooperative service model for LEO satellite operators.
  - Derive a fair revenue allocation method for participating operators during the early stages.
- Approach
  - Propose a shared satellite constellation formed by multiple LEO satellite operators.
  - Apply cooperative game theory to design a revenue-sharing method and demonstrate its effectiveness through simulation.

Assumptions

- Contract model: Fixed monthly fee
- Performance metric: Revenue
- Satellite coverage: Earth's surface divided into grid cells
- Inter-satellite communication: Possible between any satellites regardless of operator



Inter-Operator Cooperation

1. Operators in the initial stages of LEO constellation development collaborate with others.
2. Expanded coverage area, increased coverage multiplicity (number of satellites within a grid cell)
3. Higher user satisfaction
   - Broader service availability
   - Higher communication speeds due to increased coverage multiplicity
4. Increased subscription rate
5. Increased total revenue
6. Revenue Sharing
   - Distributed among operators using the Shapley value

Cooperative Game Theory

- Basic Model
  - A theoretical framework that analyzes how multiple autonomous players form coalitions and how the resulting profits are distributed among them.
- Shapley Value
  - A method for fair profit distribution based on each player's marginal contribution—the expected added value when a player joins a coalition.
- Characteristic Function v
  - A function that assigns the maximum achievable value (e.g., revenue) to each possible coalition.
- Revenue Allocation:
  - The Shapley value φ is calculated using the characteristic function v.

Modeling (Communication Range R_s, Shapley Value φ)

R_s: Communication Range of a Satellite

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

- R_e: Radius of the Earth
- H: Altitude of the satellite

N: Set of all players in the game

In a two-player game with satellite operators i and j:

$$N = \{i, j\}$$

$\varphi_i(v)$: Shapley value for operator i

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

- $v(i)$: Revenue earned by operator i (as defined by the characteristic function v)

Modeling (Characteristic Function v)

$v(i,j)$: Revenue generated when satellite operators i and j form a coalition.

$$v(i,j) = \sum_{k \in S_{all}} G_{i+j,k}$$

$$= \left(\sum_{k \in S_i \cap S_j} \alpha_{i+j,k} + \sum_{k \in S_i \cap \overline{S_j}} \alpha_{i,k} + \sum_{k \in \overline{S}_i \cap S_j} \alpha_{j,k} \right) \beta$$

- In overlapping grid cells, the number of subscribers α is jointly calculated, as the satellites form a single unified constellation.
- $G_{i,k}$: Revenue from grid cell k for operator i

$$G_{i,k} = \alpha_{i,k} \beta$$

- S_i: Set of grid cells covered by operator i
- $\alpha_{i,k}$: Number of subscribers in grid cell k for operator i
- β : Monthly subscription fee (fixed rate)

Modeling (Number of Subscribers α)

$\alpha_{i,k}$: Number of subscribers in grid cell k served by operator i

$$\alpha_{i,k} = \begin{cases} \sum_{c \in D_k} P_{k,c} C_{i,c}, & \sum_{c \in D_k} \frac{\mu_{i,k}\gamma_i}{P_{k,c} C_{i,c} U} \geq 1 \\ \frac{\mu_{i,k}\gamma_i}{U}, & \sum_{c \in D_k} \frac{\mu_{i,k}\gamma_i}{P_{k,c} C_{i,c} U} < 1 \end{cases}$$

- $P_{k,c}$: Population of country c within grid cell k
- $C_{i,c}$: Subscription rate of operator i in country c
  - $D_k = \{\mathrm{US}, \mathrm{Japan}, \cdots\}$: Set of countries present in grid cell k
- U: Average satellite data usage per subscriber (bps)
- γ_i: Bandwidth per satellite of operator i (bps)
- $\mu_{i,k}$: Coverage multiplicity of operator i in grid cell k
- $\frac{\mu_{i,k}\gamma_i}{P_{k,c} C_{i,c} U}$: Supply–Demand Ratio (Communication Capacity)

Modeling (Population P)

$P_{k,c}$: Population of country c within grid cell k

$$P_{k,c} = \lambda_{k,c}\eta_c$$

- $\lambda_{k,c}$: Area of country c within grid cell k
  - Derived from the Natural Earth dataset
- η_c: Population density of country c
  - Based on 2021 data from the World Bank

Modeling (Subscription Rate C)

$C_{\{i,c\}}$: Subscription rate of operator i in country c

$$C_{\{i,c\}} = C_{c\_min} + \frac{C_{c\_max} - C_{c\_min}}{1 + e^{-10(\varepsilon_i - 0.5)}}$$

$$F_c = \frac{P_c}{P_{US}}, C_{c\_min} = C_{US\_min} F_c, C_{c\_max} = C_{US\_max} F_c$$

- ε_i : User satisfaction of operator i (ranging from 0 to 1)
- C_{c_min} : Lower bound of subscription rate in country c
  - $C_{US\_min} (= 0)$: The lower limit of the contract rate in the US
- C_{c_max} : Upper bound of subscription rate in country c
  - $C_{US\_max} (= 0.01)$: Contract rate cap in the US
    - Based on Starlink's subscriber data
- F_c: Scaling factor
- P_c: Internet penetration rate in country c

Modeling (User Satisfaction ε)

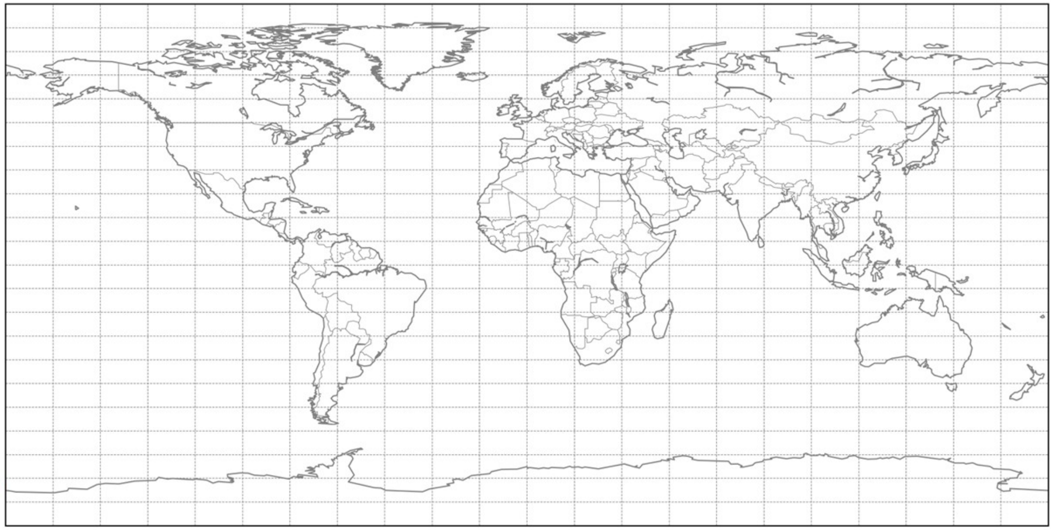
ε_i : User satisfaction for operator i (0 to 1)

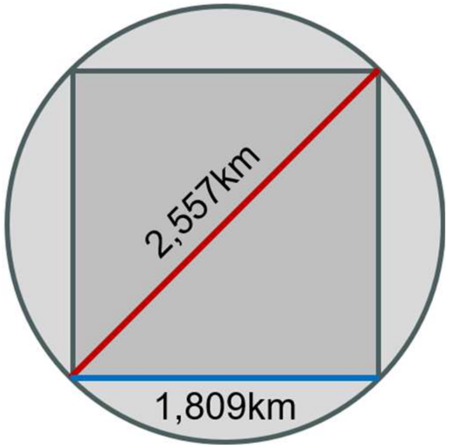
$$\varepsilon_i = \log 1.5\{\rho\omega_i + (1-\rho)\mu_i\}$$

- $\omega_i = \overline{\omega_{\{i,k\}}}$: Average coverage rate (0 to 1)
  - Reflects how often a user is within communication range
- $\mu_i = \overline{\mu_{\{i,k\}}}$: Average coverage multiplicity(0～)
  - Reflects available bandwidth due to overlapping satellite coverage
- ρ : Weighting factor (0.5 to 1)
  - Emphasizes that increased coverage rate contributes more to user satisfaction than increased multiplicity

Evaluation Conditions(1/2)

- Communication range R_s :
  Approximately 2,557 km
- Based on:
  - Earth radius $R_e \approx$ 6,371 km, Satellite altitude H = 550 km
- Grid Division of the Globe:
- The world map is divided into a 22 × 22 grid
- Each square fits inside a circle of diameter R_s
- Approximate side length of each grid cell: ~1,809 km
- Earth's circumference approximated as: ~39,798 km





Evaluation Conditions(2/2)

Assumed Cooperation Between Two Constellations:

conste1: Modeled after OneWeb (UK-based)

- Altitude: 1,200 km, Inclination: 87.9° , Orbital planes: 18, Total satellites: 648

conste2： Modeled after Qianfan (千帆) (China-based)

- Altitude: 813 km, Inclination: 89° , Orbital planes: 18, Total satellites: 648

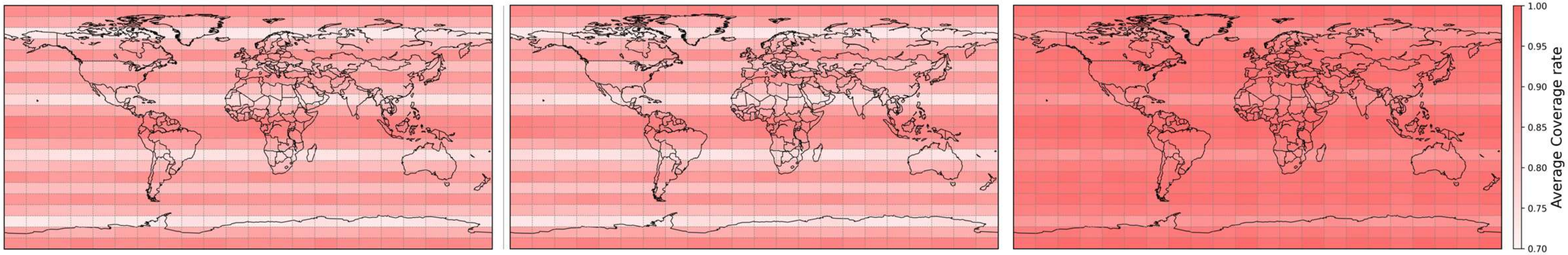
Parameters required to calculate profit

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

Coverage rate ω and coverage multiplicity μ

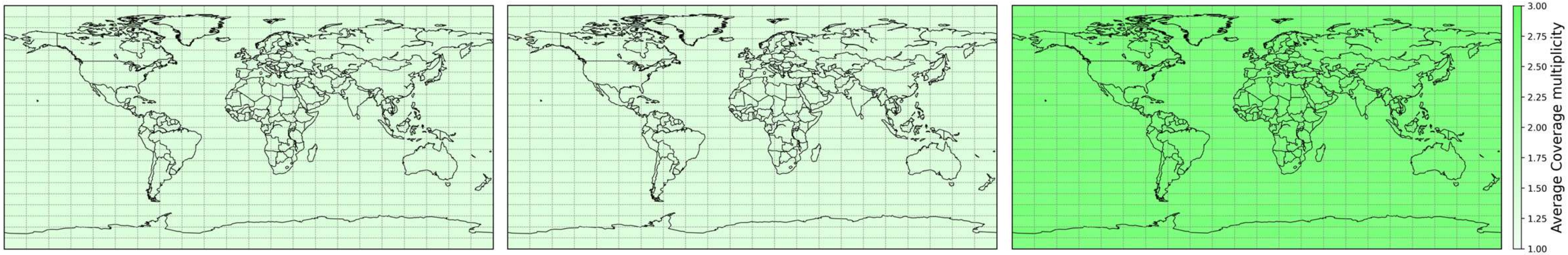
- $\omega_{c1+c2,k} > \omega_{c1,k}$, $\omega_{c2,k}$
- $\mu_{c1+c2,k} > \mu_{c1,k}$, $\mu_{c2,k}$

Coverage rate ω



$\omega_{\{c1,k\}}$ $\omega_{\{c2,k\}}$ $\omega_{\{c1+c2,k\}}$

Coverage multiplicity μ



$\mu_{\{c1,k\}}$ $\mu_{\{c2,k\}}$ $\mu_{\{c1+c2,k\}}$

Evaluation Scenarios

based on per-user traffic U

U	remarks
0.05	1/10 U_0
0.1	1/5 U_0
0.5 (= U_0)	Average smartphone usage entirely via satellite
5.0	5 U_0

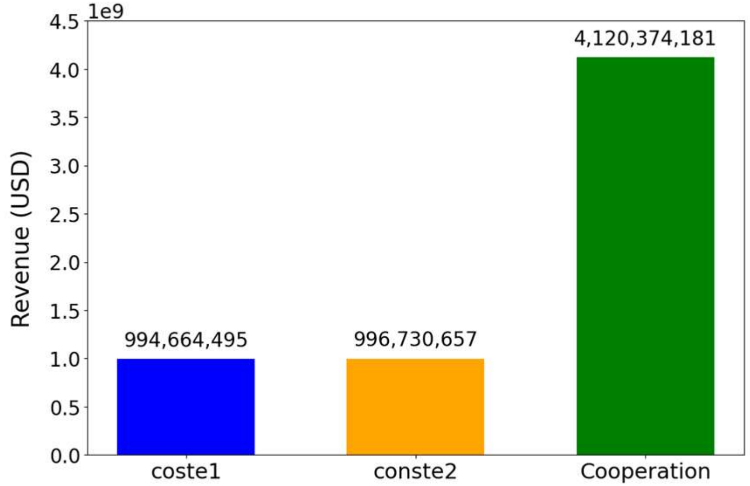
Revenue is calculated for each scenario

- If superadditivity holds:

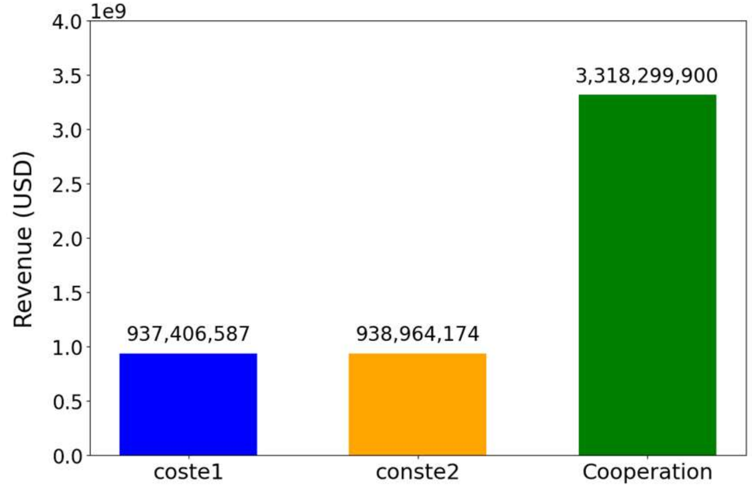
$$v(i,j) > v(i) + v(j)$$

→ Revenue is distributed using the Shapley value

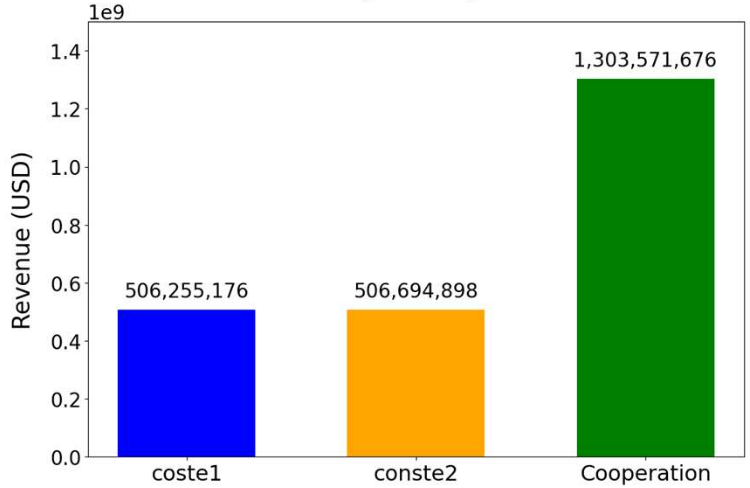
Evaluation(Revenue)



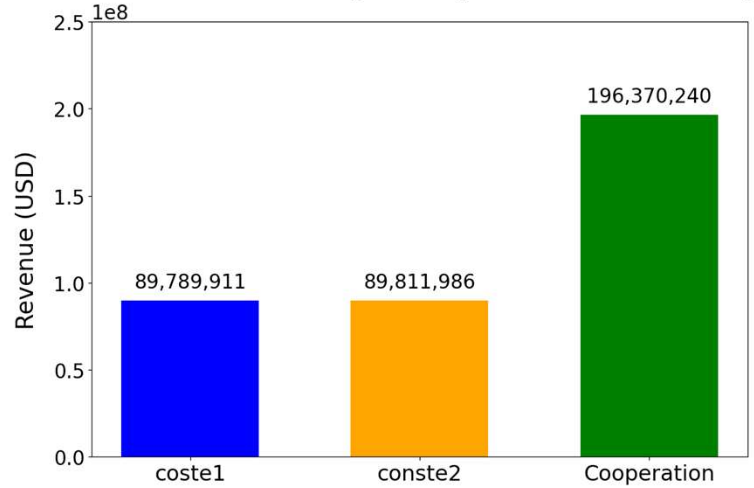
U = 0.05 Satisfy superadditivity



U = 0.1 Satisfy superadditivity



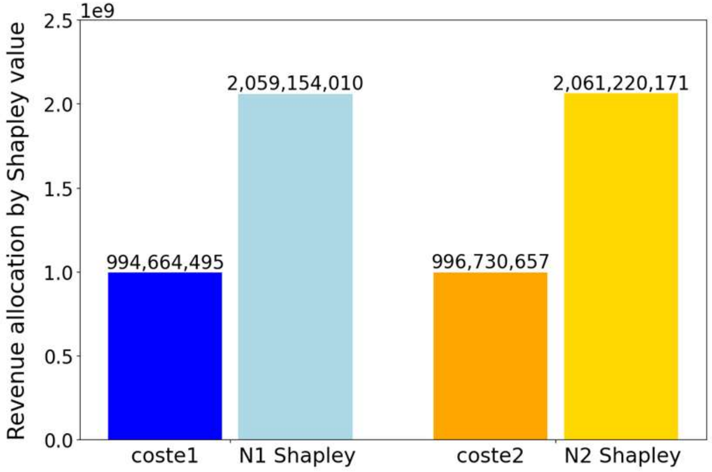
U = 0.5 Satisfy superadditivity

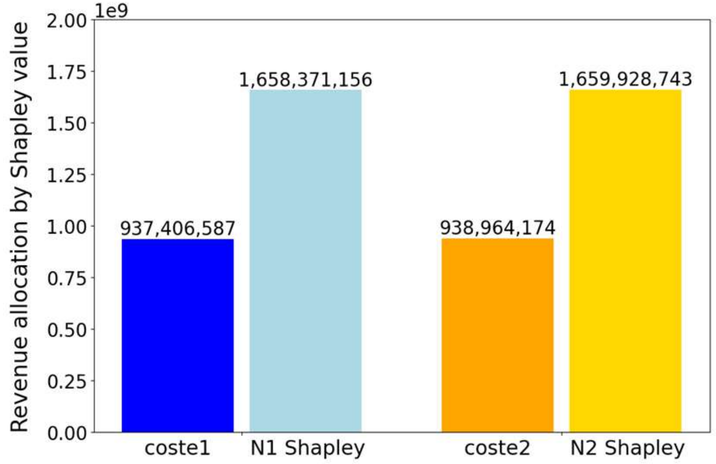


U = 5.0 Satisfy superadditivity

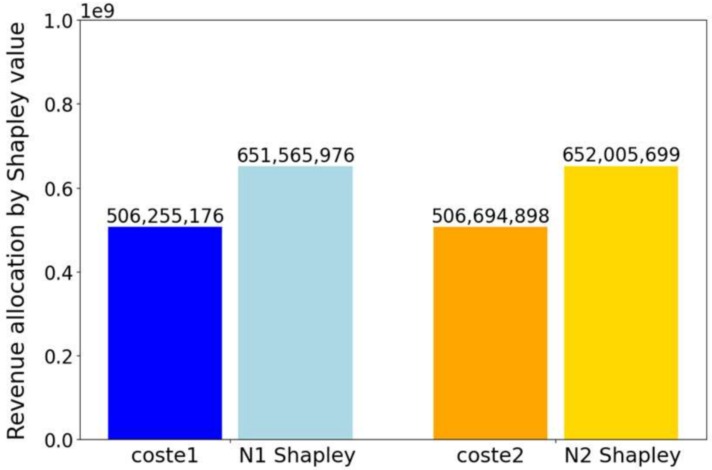
Smaller U → More users can be contracted, resulting in higher total revenue

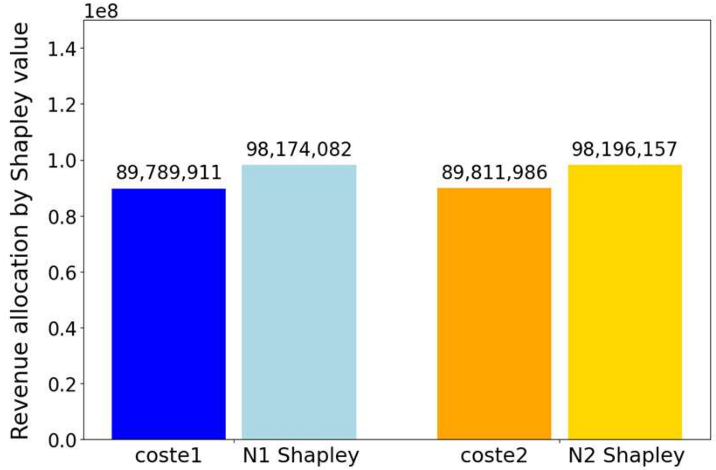
Evaluation(Shapley value)





U = 0.05 Revenue growth rate: 2.07 U = 0.1 , Revenue growth rate: 1.77





U = 0.5 , Revenue growth rate: 1.29 U = 5.0 , Revenue growth rate: 1.09

Lager U

→ Even in the non-cooperative case, demand exceeds supply in many grid cells

Conclusion and Future Work

Summary

- Proposed a cooperative model among LEO satellite operators
- Validated its effectiveness through coalition game theory and simulation
- Demonstrated that cooperation increases revenue

Challenges

- Further analysis needed on applicability conditions
- e.g., regional characteristics, demand concentration, legal environments

Future Work

- Increase the feasibility of the cooperation model in real-world scenarios
- Extend the model to more complex business environments
- Multiple stakeholders, dynamic traffic patterns, competitive markets