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An RVT-based power allocation method for dynamic LEO-MEO links①

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Abstract

Optimizing the power resources allocation method of low earth orbit (LEO) satellites to medium earth orbit (MEO) satellite' links is a significant way to construct efficient satellite constellations for satellite communication. A game theory power allocation method based on remaining visible time (RVT) of LEO-MEO satellites is proposed. Firstly, one LEO-MEO satellite network is classified as a cluster in which the RVT of LEO satellites is modeled. Secondly, the cost function of RVT concerning the character of orbit and throughput in each LEO satellite is mainly designed, which gives greater punishment of utility value to LEO satellites with less RVT and is an essential part of the reasonable utility function applied in diverse motion scenes. Meanwhile, the existence of Nash equilibrium for the proposed utility function in game theory area is proved. Thirdly, an off-cluster scheme for LEO satellites through the proposed threshold is raised to ensure the overall utility value of the whole LEO satellites in cluster. Finally, the performance improvement of the proposed algorithm to the baseline algorithm is verified through simulations in different scenarios.

Key words: inter-satellite link, power allocation, remaining visible time(RVT), utility function, motion trajectory(MT), game theory

0 Introduction

Non-terrestrial network is used to cover the remote areas where terrestrial network could not serve, and is treated as an extension of terrestrial network[1-2]. However, due to limitations of market access, limited frequency resources, and insufficient international competition for satellite communication areas, only 3372 satellites on orbit were cataloged in January 2021 globally[3], which is far short of quantities compared with terrestrial network. Therefore, how to make full use of limited satellite resources and inherent high dynamic characteristics of the on-orbit satellites due to low altitude, and how to build valid satellite constellations for interconnection are all big challenges to work.

A whole inter-satellite network is composed of plenty of low earth orbit-medium earth orbit (LEO-MEO) satellite networks. There is one MEO satellite as manager who is responsible for regulating and communicating with several LEO satellites in the same LEO-MEO satellite network, in which LEO satellites send data packets, such as routing tables or congestion control data, to MEO satellite, and interact with ground users. MEO satellite forwards the information collected from LEO satellites to the associated MEO management satellite.

At present, most scholars optimized the performance of power resources allocation in LEO satellites from the perspective of the satellite-ground downlink. Ref. [4] aimed at quality of service requirements and backhaul capacity, and proposed a power allocation method and a relay selection policy which highly enhanced the system performance. Nevertheless, the co-channel interference was not considered. Ref. [5] took co-channel interference into account and proved the NP-hard characteristics of the multi-beam power allocation problem, for which scholars were inspired with a heuristic algorithm to transform matter into a two-stage optimization model and attained performance improvement to some extent. Other scholars made optimization to power resources allocation of inter-satellite links in satellites constellation network. Ref. [6] continued to employ relay in inter-satellite links on the basis of Ref. [4], and studied a relay satellite system that included one GEO satellite and several LEO/MEO satel-

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lites. The power resources allocation of inter-satellite links was modeled as a problem of maximizing energy efficiency, which was worked out through Lagrange duality method. Ref. [7] proposed a dynamic power allocation method for inter-satellite links of LEO/MEO satellites. The inter-satellite link distance was predicted by spherical geometric relationship between LEO/MEO satellites, which could further estimate the signal-to-interference-noise ratio (SINR) in advance, thereby reducing the channel detection time. However, Ref. [6] only considered a static model, and Ref. [7] merely took one scenario as LEO satellites approaching MEO satellite into account. Refs[6,7]did not extend to diverse motion scenes. Ref. [8] proposed an optimal capacity allocation algorithm in a three-layer heterogeneous satellite network, giving the dynamic scenarios, but the issue of power resources allocation had not been related at the same scenes.

Considering such diverse scenarios during which LEO satellites cannot correspond with MEO satellite in the current network momently, in case these LEO satellites are still allocated power resources unexpectedly, it will cause not only much resource waste but also other side effects as well as interference, etc. Therefore, it is necessary to indicate these LEO satellites off the located network in time, that is to say, not to provide any service to such LEO satellites in the previous network. Two satellite handover techniques based on shortest path and correlated service time are used in LEO satellites handover process[9-10], but it is unsuitably employed in scenarios with unstable communication links due to the edge of line-of-sight.

To this end, the power allocation method proposed in this paper, which can be applied to diverse motion scenes, could both guarantee performance and quantities of serving LEO satellites in the current LEO-MEO satellite network to the greatest extent, alongside avoiding the exceptional condition in which LEO satellite is still in the current network, but cannot communicate due to departure from line-of-sight to MEO satellite. The main contributions are summarized as follows.

(1) The penalty of utility value with LEO-MEO remaining visible time (RVT) is mainly devised by considering the height of operating orbit and the throughput of LEO satellites, to give a greater utility punishment to such LEO satellites with less RVT. If the channel quality of an LEO satellite is relatively good, penalization would reduce correspondingly. On the other hand, if the LEO satellite will be out of line-of-sight immediately, the penalty would increase extraordinarily. Meanwhile, the existence of Nash equilibrium of the proposed utility function based on RVT is proved, so that it can be accessibly applied in game theory.

(2) The threshold which depends on the ratio of current LEO satellite throughput revenue and energy penalty is defined, and an off-cluster scheme for LEO satellite is designed through this threshold further. It makes the LEO satellite whose utility value is lower than the threshold out of the current cluster. If the weight of throughput revenue is larger, LEO satellites would easily stay in cluster. Instead, they would be willing to leave cluster.

(3) To prove the effectiveness of the proposal, experiments are carried out with the proposed algorithm and baseline algorithms for comparison. Simulation results show the performance enhancement with the proposed algorithm in different scenarios.

The remainder of this work is organized as follows.

The system model and optimization problem are introduced in Section 1. The utility function based on RVT and off-cluster scheme are proposed in Section 2, and the existence of Nash equilibrium of the utility function is also proved in this section. Section 3 gives a theoretical analysis of the simulation results. Section 4 remarks on the conclusion of work.

1 System model

Satellites constellation network comprises several LEO-MEO satellite networks. One LEO-MEO satellite network in a constellation is highlighted with grey color in Fig. 1. Let $I = \{1, 2, \cdots, n\}$ and $J = \{1\}$ denote the sets of LEO satellites and MEO satellite in the marked network. Both collection I and J constitute one cluster in which the members of MEO and LEO satellites are separately classified as cluster head and nodes. The same cluster nodes can be applied business support, such as allocating power resources, bandwidth resources and communication by head. In view of this, the proposal below mainly considers the MEO and LEO satellites within the same cluster.

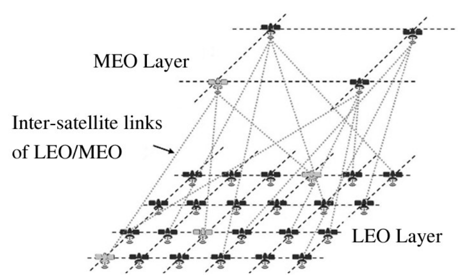


Fig. 1 Abstracted satellites constellation graph

Since satellite periods of revolution differ in height of the operating orbits, there should be a case in which LEO and MEO satellites respectively keep out of line-of-sight each during a period of time. However, owing to specific property of inter-satellite links, it is determined that information transmission among satellites mainly depends on the line-of-sight transmission channel[11]. So it is necessary to partition the on-orbit motions of satellites into different features due to the high dynamic mobility of satellites, to exclude the out-of-service situations in advance.

1.1 RVT model

Let orbital radiuses of LEO satellites in set I be $\{r_1, r_2, \cdots, r_n\}$, orbital radius of MEO satellite in set J be $\{R_1\}$, and corresponding geocentric angle between LEO and MEO be $\{\varphi_{11}, \varphi_{12}, \cdots, \varphi_{1n}\}$. Although the orbit of a satellite is not a strict circle, regarding orbit as a circle does not affect the model's applicability due to a slight error estimate caused at the condition of a distance of thousand kilometers for inter-satellite link. Therefore, the inter-satellite link distance and geocentric angle between the i^{th} LEO satellite and MEO satellite meet the following requirement mathematically.

$$L_{1i}(t) = [R_1^2 + r_i^2 - 2R_1 r_i \cos\varphi_{1i}(t)]^{1/2}, \ 1 \leqslant i \leqslant n \quad (1)$$

$$\varphi_{1i}(t) = \arccos[\sin X_1(t)\sin x_i(t) + \cos X_1(t)\cos x_i(t)\cos(Y_1(t) - y_i(t))], \quad -\pi \leqslant \varphi_{1i}(t) \leqslant \pi \quad (2)$$

where, $Y_1(t)$ and $X_1(t)$ respectively denote the latitude and longitude of the MEO satellite, $y_i(t)$ and $x_i(t)$ separately indicate the latitude and longitude of the i^{th} LEO satellite. Since satellite moves around earth in an approximately uniform circular motion, the relationship between latitude/longitude and time obeys the linear change periodically. Thus duration and link distance following the periodic law can be easily got:

$$\frac{\mathrm{d}L_{1i}(t + k\Gamma_i)}{\mathrm{d}t} = -\frac{R_1 r_i \sin\varphi_{1i}(t + k\Gamma_i)}{\sqrt{R_1^2 + r_i^2 - 2R_1 r_i \cos\varphi_{1i}(t + k\Gamma_i)}} \cdot \frac{\mathrm{d}\varphi_{1i}(t + k\Gamma_i)}{\mathrm{d}t} \quad (3)$$

in which Γ_i denotes a period of relative motion between the i^{th} LEO and MEO satellite, k presents natural number. Further more, it can be seen that when $\mathrm{d}\varphi_{1i}(t + k\Gamma_i)/\mathrm{d}t = 0$, the inter-satellite link distance is either shortest or longest. Since the longest distance belongs to the state which is precluded previously due to the satellites being out of line-of-sight, the moment for the shortest distance recorded as $t_{\min}$ is used as the dividing point. According to spherical geometry, when the line of vision between LEO and MEO satellite is tangent to earth's spherical surface, it reveals that the LEO satellite is about to enter the visible area or invisible area to MEO satellite. Thus this model presents a concept for RVT of LEO-MEO satellites, where the parameter of T_i^{rem} for RVT of the i^{th} LEO satellite in cluster is defined as

$$\begin{cases} t_{\min} < T_i^{\text{rem}} < |t_{i2} - t_{i1}| & \text{sufficient RVT} \\ 0 < T_i^{\text{rem}} < t_{\min} & \text{insufficient RVT} \end{cases} \quad (4)$$

where, t_{i1} and t_{i2} are the moments when the i^{th} LEO satellite adjacently enters and leaves the visible area of MEO satellite, $|t_{i2} - t_{i1}|$ is the maximum of RVT, all of which meet Eq. (5).

$$L_{1i}(t_{i1}) = L_{1i}(t_{i2}) = \sqrt{R_1^2 - r^2} + \sqrt{r_i^2 - r^2} \quad \text{s.t.} \ |t_{i2} - t_{i1}| < \Gamma_i \quad (5)$$

herein, r means the earth radius. Since period of MEO satellite is several times longer than LEO satellite, the maximum of RVT is lower than Γ_i.

Hence, the integrated motion trace of a LEO satellite can be dividedly simplified into

$$\left\{ \begin{array}{c} \text{Path}_1 \,|_{t_{\min} < T_i^{\text{rem}} < |t_{i2} - t_{i1}|}, \ \text{Path}_2 \,|_{0 < T_i^{\text{rem}} < t_{\min}}, \\ \text{Path}_3 \,|_{T_i^{\text{rem}} = 0} \end{array} \right\} \quad (6)$$

where Path_1 denotes the i^{th} LEO satellite begins in moving into the visible area of MEO satellite and ends in reaching the shortest distance to MEO satellite. Path_2 denotes the i^{th} LEO satellite begins in reaching the shortest distance to MEO satellite and ends in entering into the invisible area of MEO satellite. The remaining Path_3 implies that the i^{th} LEO satellite absolutely locates in the invisible area of MEO satellite.

A consecutive motion trajectory (MT) for the i^{th} LEO satellite which can communicate with MEO satellite normally in the same cluster is simplified as MT_i.

$$\text{MT}_i \subseteq \{\text{Path}_1 \,|_{t_{\min} < T_i^{\text{rem}} < |t_{i2} - t_{i1}|}, \ \text{Path}_2 \,|_{0 < T_i^{\text{rem}} < t_{\min}}\} \quad (7)$$

Evidently, T_i^{rem} gradually decreases with time lapses. In order to analyze the dynamic characteristics of LEO satellites based on RVT, this model evenly selects a number of times $\{t_k, \ k \in \{1, 2, \cdots, N\}\}$ which should cover the typical locations, such as the critical points, to obviously demonstrate the influence of different motion scenes. The interval between two adjacent sampling moments is recorded as Δt. After each sampling moment T_i^{rem} is updated as

$$T_i^{\text{rem}} \leftarrow T_i^{\text{rem}} - \Delta t \quad (8)$$

It is noteworthy that if RVT is updated to a negative value, T_i^{rem} should be set to zero practically.

1.2 Problem formulation

Assuming that the MEO satellite provides service support to n LEO satellites in cluster simultaneously, for MEO satellite, the received power at time t_k coming from the i^{th} LEO satellite is defined as

$$p_{ri}(t_k) = \frac{\lambda^2}{16\pi^2} G_r G_i L_{1i}^{-2}(t_k) p_i(t_k),\ 1 \leqslant i \leqslant n \tag{9}$$

where, $p_i(t_k)$ is the transmission power of the i^{th} LEO satellite at time t_k, G_i is the gain of the transmit antenna for the i^{th} LEO satellite, G_r is the gain of the receive antenna for MEO satellite, λ is the wavelength of the transmitted signal.

Since the coefficient $\lambda^2 G_r G_i L_{1i}^{-2}(t_k)/16\pi^2$ only relates to time t_k, namely the coefficient is a constant, as long as the time is fixed. So the received power can be simplified as

$$p_{ri}(t_k) = h_i(t_k) p_i(t_k),\quad 1 \leqslant i \leqslant n \tag{10}$$

Let $\boldsymbol{h}(t_k) = [h_1(t_k)\quad h_2(t_k)\ \cdots h_n(t_k)]$ be the parameter of channel gains for inter-satellite links, where

$$h_i(t_k) = \lambda^2 G_r G_i L_{1i}^{-2}(t_k)/16\pi^2 \tag{11}$$

Therefore, the SINR of MEO satellite from all n LEO satellites in cluster at time t_k is defined as

$$\begin{aligned}\boldsymbol{\xi}(t_k) &= [\xi_1(t_k)\quad \xi_2(t_k)\quad \cdots\quad \xi_n(t_k)] \\ &= \Big[\frac{h_1(t_k)p_1(t_k)}{\sigma^2 + \sum_{i\neq 1}^{n} h_i(t_k)p_i(t_k)}\quad \frac{h_2(t_k)p_2(t_k)}{\sigma^2 + \sum_{i\neq 2}^{n} h_i(t_k)p_i(t_k)} \\ &\quad \cdots\quad \frac{h_n(t_k)p_n(t_k)}{\sigma^2 + \sum_{i\neq n}^{n} h_i(t_k)p_i(t_k)}\Big]\end{aligned}$$

in which $\xi_i(t_k)$ denotes the SINR of MEO satellite from the i^{th} LEO satellite at time t_k, σ^2 is thermal noise power.

Obviously, increasing transmission power of LEO satellite will improve the corresponding SINR of MEO satellite for earning a throughput profit, nevertheless, it will distract other LEO satellites in the same cluster and reduce related SINR. On the other side lifting transmission power casually will also cause much energy consumption and shorten service time on-orbit of itself.

The main quality-of-service requirement of network is typically given by throughput requirement[12], hence, the target of this model is to optimize the overall throughput performance for all LEO satellites in cluster with diverse motion scenes, which meets the following requirements.

$$\text{P0}:\ \max_{p_i} B\sum_{i=1}^{n} \log(1 + \xi_i(t_k)) \tag{13a}$$

$$\text{s.t.}\quad \text{Eq. (7)}$$

$$p_{\min} \leqslant p_i \leqslant p_{\max} \tag{13b}$$

$$\sum_{j\neq i}^{n} h_j(t_k)p_j(t_k) \leqslant I_{th} \tag{13c}$$

where I_{th} is the threshold of the total interference power which depends on the anti-jamming capacity of demodulation at MEO satellite, composition of several MT_i generates different motion scenes; $p_{\max}$ and $p_{\min}$ are the boundaries of transmission power for LEO satellites; P0 is a non-convex optimization problem, that is, it becomes more challenging when further added to diverse motion scenes.

2 Proposed algorithm

Game theory explores the influence of incentive mechanism on users' behaviors in network mathematically[13], which could reach an agreement called Nash equilibrium in non-cooperative game that no user can improve its performance by breaking such the deal. Therefore, game theory also plays a guiding role in how to allocate network resources fairly and reasonably[14].

When game theory is applied to satellite communication area, the three main components of the game are named as participants, strategies, and benefits[15]. Participants are composed of all LEO satellites in cluster. Adjusting transmission power is the strategy employed by participant and the benefits are satellites' throughput gains or other performance indicators.

The game model is expressed as

$$G = [N, \{p_i\}, \{u_i\}] \tag{14}$$

where, $N = \{1, 2, \cdots, n\}$ denotes the set of participants of LEO satellites in cluster, $\{p_i\}$ is the set of transmission powers of LEO satellites, and $\{u_i\}$ represents the set of utility values of LEO satellites.

The utility function designed in this paper perceives that the throughput of LEO satellites referring to Eq. (13a) has a significantly positive impact on utility value, and both energy consumption and RVT of LEO satellites have negative impressions. The purpose of setting energy consumption is to reduce incline for LEO satellites adopting larger power blindly according to Eqs(13b), (13c), and the intention to define RVT is to adapt LEO satellites to diverse motion scenes referring to Eq. (7).

Next, the design of utility function is introduced in detail, parameters of $\boldsymbol{R}^{\text{tput}}$, $\boldsymbol{C}^{\text{engy}}$ and $\boldsymbol{C}^{\text{time}}$ are used to represent the revenue and the cost of utility respectively.

2.1 Design of utility function

The normalized throughput of n LEO satellites in cluster at time t_k is defined as

$$\begin{aligned}\boldsymbol{C} &= [C_1(t_k, p_1(t_k), p_{\bar{1}}(t_k))\quad C_2(t_k, p_2(t_k), p_{\bar{2}}(t_k)) \\ &\quad \cdots\quad C_n(t_k, p_n(t_k), p_{\bar{n}}(t_k))] \\ &= \beta\cdot[B\log(1 + \xi_1(t_k))\quad B\log(1 + \xi_2(t_k))\end{aligned}$$

$$\cdots \quad B\log(1+\xi_n(t_k))] \tag{15}$$

in which, $p_{\bar{i}}(t_k)$ is the transmission power of each LEO satellite except the i^{th} LEO satellite at time t_k, B is the co-channel bandwidth of LEO satellites, and β is the normalization factor as the following definition.

$$\beta = 1/[B\log(1+\xi_{\max})] \tag{16}$$

where $\xi_{\max} = p_{\max}/\sigma^2$.

Therefore, the revenue function of LEO satellites is defined based on normalized throughput at time t_k as

$$\begin{aligned}\boldsymbol{R}^{tput} &= [R_1^{tput}(t_k, p_1(t_k), p_{\bar{1}}(t_k)) \\ &\quad R_2^{tput}(t_k, p_2(t_k), p_{\bar{2}}(t_k)) \\ &\quad \cdots \quad R_n^{tput}(t_k, p_n(t_k), p_{\bar{n}}(t_k))] \\ &= \zeta \cdot [C_1(t_k, p_1(t_k), p_{\bar{1}}(t_k)) \\ &\quad C_2(t_k, p_2(t_k), p_{\bar{2}}(t_k)) \\ &\quad \cdots \quad C_n(t_k, p_n(t_k), p_{\bar{n}}(t_k))]\end{aligned} \tag{17}$$

where ζ is the revenue factor of throughput, since it is the only positive incentive of utility, more weight should be given to throughput by setting $\zeta = 1$.

The normalized energy consumption of n LEO satellites in cluster at time t_k is defined as

$$\begin{aligned}&\boldsymbol{E} = \\ &[E_1(t_k, p_1(t_k)) \quad E_2(t_k, p_2(t_k)) \quad \cdots \quad E_n(t_k, p_n(t_k))] \\ &= \gamma \cdot [\int_{t_k}^{t_k+\Delta t} p_1(t_k)\mathrm{d}t \quad \int_{t_k}^{t_k+\Delta t} p_2(t_k)\mathrm{d}t \quad \cdots \quad \int_{t_k}^{t_k+\Delta t} p_n(t_k)\mathrm{d}t]\end{aligned} \tag{18}$$

where Δt is the length between two adjacent sampling moments, and γ is the normalization factor as

$$\gamma = 1/\int_0^{t_{\max}} p_{\max}\mathrm{d}t \tag{19}$$

where $t_{\max}$ refers to the longest time for which LEO satellite can continue operating with maximum transmission power.

Therefore, the first section of cost function is defined based on normalized energy consumption at time t_k as below:

$$\begin{aligned}\boldsymbol{C}^{engy} &= [C_1^{engy}(t_k, p_1(t_k)) \quad C_2^{engy}(t_k, p_2(t_k)) \\ &\quad \cdots \quad C_n^{engy}(t_k, p_n(t_k))] \\ &= [\eta E_1(t_k, p_1(t_k)) \quad \eta E_2(t_k, p_2(t_k)) \\ &\quad \cdots \quad \eta E_n(t_k, p_n(t_k))]\end{aligned} \tag{20}$$

where η is the penalty factor of energy consumption.

Since

$$\int_0^{t_{\max}} p_{\max}\mathrm{d}t >> \int_{t_k}^{t_k+\Delta t} p_i(t_k)\mathrm{d}t \tag{21}$$

η should be taken as a relatively large numerical for aiming to improve the influence of punishment with energy consumption on utility. On the other side, assuming that if LEO satellite is under such a situation with good channel condition and low interference to others, this satellite should more incline to transmit with maximum power to improve the only gain of throughput, if possible. So taking into account both revenue and cost, η should meet:

$$\eta\int_{t_k}^{t_k+\Delta t} p_{\max}\mathrm{d}t \approx 0.5 \tag{22}$$

Finally, the RVT of n LEO satellites in cluster at time t_k is defined as

$$\begin{aligned}\boldsymbol{T}_i^{rem} &= [T_1^{rem}(t_k) \quad T_2^{rem}(t_k) \quad \cdots \quad T_n^{rem}(t_k)] \\ &= [t_{10} - (k-1)\Delta t,\ t_{20} - (k-1)\Delta t,\ \cdots, \\ &\quad t_{n0} - (k-1)\Delta t]\end{aligned} \tag{23}$$

where t_{10}, t_{20}, $\cdots$, t_{n0} are the initial RVT for LEO_1, LEO_2, $\cdots$, LEO_n satellites. Since the first sampling time is recorded as the initial time, the k^{th} sampling time elucidates that the LEO satellite has gone through a certain time of $(k-1)\Delta t$.

Accordingly the second portion of cost function, which is a significant part of utility function applying to diverse motion scenes, is defined based on RVT at time t_k as

$$\begin{aligned}&\boldsymbol{C}^{time} \\ &= [C_1^{time}(t_k, p_1(t_k), p_{\bar{1}}(t_k)) \quad C_2^{time}(t_k, p_2(t_k), p_{\bar{2}}(t_k)) \\ &\quad \cdots \quad C_n^{time}(t_k, p_n(t_k), p_{\bar{n}}(t_k))] \\ &= [\frac{k_{12}}{e^{k_{11}[t_{10}-(k-1)\Delta t+t_G]}-1} \quad \frac{k_{22}}{e^{k_{21}[t_{20}-(k-1)\Delta t+t_G]}-1} \\ &\quad \cdots \quad \frac{k_{n2}}{e^{k_{n1}[t_{n0}-(k-1)\Delta t+t_G]}-1}]\end{aligned} \tag{24}$$

Factor k_{i1} ($i \in \{1, 2, \cdots, n\}$) is a convergence coefficient of RVT for the i^{th} LEO satellite, determining the speed of RVT cost function ' s convergence. The value of k_{i1} depends on the cycle of satellite, and satisfies:

$$k_{i1} = s_1/T_i \tag{25}$$

where, $s_1 = \min T_j (j \in I)$, T_i denotes period of the i^{th} LEO satellite. Obviously, the less the period of a satellite is, the faster convergence of RVT cost function will be. In other words, it implies that the higher the dynamical satellite is, the larger scale of strategy adjustment will be executed.

Factor k_{i2} ($i \in \{1, 2, \cdots, n\}$), a penalty coefficient of RVT for the i^{th} LEO satellite, determines the degree of penalty of RVT cost function. The value of k_{i2} depends on the moment throughput, which is positively associated with SINR, and satisfies:

$$k_{i2} = | s_2/\xi_i(t_k) | \tag{26}$$

where $s_2 = \min\xi_j(t_k)$ $(j \in I)$. Noticeably, the higher the throughput is, the minor value of RVT cost function will be. That is to say, the better the channel quality is, the less punishment will be imposed. Thus, it can realize a full use of value for LEO satellite in its insufficient RVT.

Note that, if the RVT of LEO satellite is abundant or slightly insufficient, the penalty of RVT could be approximately ignored, satisfies:

$$\frac{k_{i2}}{e^{k_{i1}(t_{i0}+t_G)}-1} \xrightarrow{t_{i0} >> 0} 0 \tag{27}$$

On the contrary, if the RVT of LEO satellite is out, the absolute value of RVT penalty satisfies:

$$k_{i2}/(e^{k_{i1}\cdot t_G}-1) > 1 \tag{28}$$

That is to say, it is punished by a particularly large utility value. t_G denotes the time guard interval, which avoids the penalty value tending to infinity.

To sum up, the utility values of n LEO satellites in cluster at time t_k satisfies:

$$\boldsymbol{U} = [u_1(t_k, p_1(t_k), p_{\bar{1}}(t_k)) \quad u_2(t_k, p_2(t_k), p_{\bar{2}}(t_k)) \quad \cdots \quad u_n(t_k, p_n(t_k), p_{\bar{n}}(t_k))] \tag{29}$$

where

$$u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k)) = R_i^{\text{tput}}(t_k, p_i(t_k), p_{\bar{i}}(t_k)) - C_i^{\text{engy}}(t_k, p_i(t_k)) - C_i^{\text{time}}(t_k, p_i(t_k), p_{\bar{i}}(t_k)) \tag{30}$$

2.2 Off-cluster scheme

In order to maximize the overall utility value $u_{\text{total}}(t_k)$ of LEO satellites in cluster at time t_k, the P0 problem according to Eq. (13) can be redefined as

$$\max_{p_i \in \mathbb{P}} u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k)), \ i \leqslant n \tag{31a}$$

$$\text{s.t.} \quad \forall U_i(t_k, p_i(t_k), p_{\bar{i}}(t_k)) > \text{threshold}, \quad 1 \leqslant i \leqslant l \tag{31b}$$

$$u_{\text{total}}(t_k) = \begin{cases} \sum_{i=1}^{l} U_i(t_k, p_i(t_k), p_{\bar{i}}(t_k)) & l \geqslant 1 \\ 0 & l = 0 \end{cases} \tag{31c}$$

Herein, Eq. (31a) is worked out through the designed utility function based on non-cooperative game by searching for Nash equilibrium. $\mathbb{P}$ is a set of valid transmission powers, U_i is the filtered utility value who is higher than threshold. The off-cluster threshold for any i^{th} LEO satellite maintained in cluster depends on the ratio of current throughput revenue and energy penalty, meets:

$$\text{threshold} = -\frac{R_i^{\text{tput}}(t_k, p_i(t_k), p_{\bar{i}}(t_k))}{C_i^{\text{engy}}(t_k, p_i(t_k))} \cdot \mu \tag{32}$$

where $\mu (0.01 \leqslant \mu \leqslant 0.5)$ is the weight factor which is used to balance the influence of throughput benefit and energy penalty. If the weight of throughput revenue is larger, LEO satellites would prefer to stay in cluster. Whereas, if the other part is larger, LEO satellites would be impatient and leave cluster more easily. Generally $\mu = 0.25$ is taken as a compromise.

2.3 Proof of convergence

In accordance with Nash equilibrium existence theorem:

$$u_i(t_k, p_i^*(t_k), p_{\bar{i}}^*(t_k)) \geqslant u_i(t_k, p_i(t_k), p_{\bar{i}}^*(t_k)) \tag{33}$$

Eq. (33) can be regarded as the best power allocation approach for each participant in this game. According to the existence of Nash equilibrium, the independent variable p_i in utility function is a non-empty compact convex subset in Euclidean space, and the system utility function is either quasi-convex or quasi-concave within the interval of an independent variable, then the existence of pure strategy for Nash equilibrium has been proved[16].

Proof

(1) Whatever is the transmission power, its value always exists naturally. Moreover, $\boldsymbol{P}$ is a non-empty compact convex subset in Euclidean space due to $\boldsymbol{P} = \{p_1, p_2, \cdots, p_n\}$, $p_{\min} \leqslant p_i \leqslant p_{\max}$.

(2) By utilizing Eqs(17), (20), (24) and (29), it can be obtained as

$$u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k)) = \zeta\beta\log(1+\xi_i(t_k, p_i)) - \eta\gamma\int_{t_k}^{t_k+\Delta t} p_{ti}(t_k)\,\mathrm{d}t - \frac{s_2/\xi_i(t_k, p_i)}{e^{s_1[t_{i0}-(k-1)\Delta t+t_G]/T_i}-1} \tag{34}$$

Find the first-order partial derivative of u_i:

$$\frac{\partial u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k))}{\partial p_i(t_k)} = \frac{\zeta\beta}{\ln 2} \cdot \frac{h_i(t_k)}{h_i(t_k)p_i(t_k)+\sigma^2+N} - \eta\gamma p_i(t_k) + \frac{s_2}{e^{s_1[t_{i0}-(k-1)\Delta t+t_G]/T_i}-1} \cdot \frac{\sigma^2+N}{h_i(t_k)p_i^2(t_k)} \tag{35}$$

Then obtain the second-order partial derivative of u_i:

$$\frac{\partial^2 u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k))}{\partial p_i^2(t_k)} = -\frac{\zeta\beta}{\ln 2} \cdot \frac{h_i^2(t_k)}{[h_i(t_k)p_i(t_k)+\sigma^2+N]^2} - \eta\gamma - \frac{s_2}{e^{s_1[t_{i0}-(k-1)\Delta t+t_G]/T_i}-1} \cdot \frac{\sigma^2+N}{h_i(t_k)p_i^3(t_k)} \tag{36}$$

Since each part of Eq. (36) is negative distinctly, a conclusion could be easily drawn as Eq. (37).

$$\frac{\partial^2 u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k))}{\partial p_i^2(t_k)} < 0 \tag{37}$$

Therefore, the quasi-concavity of the system utility function is proved, so that the existence of Nash equilibrium point has been acquired.

2.4 Algorithm flow

The design procedures and steps of game theory based on RVT are summarized as Algorithm 1.

The progress of off-cluster scheme is shown as Algorithm 2.

Algorithm 1 Game theory based on RVT

Input: G_r, G_i, L_{1i}, LEO satellites number N, range of LEO satellite's transmission power $[p_{\min}, p_{\max}]$, step size of transmission power Δp, set of valid transmission powers $\mathbb{P} = \{p_{\min}, p_{\min}+\Delta p, \cdots, p_{\max}-\Delta p, p_{\max}\}$, $\forall i \in I = \{1, 2, \cdots, N\}$, $\forall p_i(t, m) \in \mathbb{P}$, $\forall m \in \{1, 2, \cdots, (p_{\max} - p_{\min})/\Delta p\}$, user's RVT t_{i0}, current time t.

Output: $u_{\text{total}} = \sum_1^N u_i$, $\boldsymbol{P} = \{p_1(t), p_2(t), \cdots, p_N(t)\}$.

Initialization: set t to feasible value, update RVT by Eqs(1), (2), set temporary independent variable $p_i(t, m)$;

Repeat for i

Repeat for $p_i(t, m)$

1) update $R_i^{\text{tupt}}(t, p_i(t), p_{\bar{i}}(t))$ by Eqs(15), (17);

2) update $C_i^{\text{engy}}(t, p_i(t))$ by Eqs(18), (20);

3) update $C_i^{\text{time}}(t, p_i(t), p_{\bar{i}}(t))$ by Eqs(24), (25), (26);

4) update $u_i(t, p_i(t), p_{\bar{i}}(t))$ by Eq. (30);

until satisfaction

$$p_i(t, j)\frac{\partial u_i}{\partial p_i(t, j)} = 0 \tag{38}$$

5) replace the temporary independent variable

$$p_i(t) = p_i(t, j) \tag{39}$$

6) update $\boldsymbol{P}$;

until convergence $| p_i(t, j) - p_i(t, j-1) | < \Delta p$

update u_{total}

$$u_{\text{total}}(t) = \sum_{i=1}^{N} u_i(t, p_i(t), p_{\bar{i}}(t)) \tag{40}$$

Algorithm 2 Off-cluster scheme

Input: initial LEO satellites number N, weight factor of threshold μ, set of sampling time $\forall t_k \in \{t_{\min}, t_{\min}+\Delta t, \cdots, t_{\max}-\Delta t, t_{\max}\}$, user's RVT t_{i0}.

Output: $u_{\text{total}}^{\text{final}}(t_k, p_i(t_k), p_{\bar{i}}(t_k))$, $\boldsymbol{P}^{\text{final}}(t_k)$.

Repeat

Initialization: $u_{\text{total}}(t_k, p_i(t_k), p_{\bar{i}}(t_k)) = \sum_1^N u_i(t_k, p_i(t_k), p_{\bar{i}}(t_k))$ by calling Algorithm 1;

Repeat

1) update $R_i^{\text{tupt}}(t_k, p_i(t_k), p_{\bar{i}}(t_k))$ and $C_i^{\text{engy}}(t_k, p_i(t_k))$ by calling Algorithm 1;

2) update each threshold of off-cluster by Eq. (32);

3) Eliminate user whose utility value is lower than the threshold;

until utility value of each user in cluster is higher than each threshold;

4) update $\boldsymbol{P}^{\text{final}}(t_k)$ by calling Algorithm 1;

5) update $u_{\text{total}}^{\text{final}}(t_k)$ by calling Algorithm 1;

6) update current time

$$t_k = t_k + \Delta t \tag{41}$$

7) update users' RVT by Eq. (8);

until $t_k > t_{\max}$

Here, the complexity of the iterative Algorithm 1 is $O(NM)$, where N is the number of LEO satellites in cluster, M is the number of quantized powers. For Algorithm 1, its complexity is lower than water-filling algorithm which is $O(N^2M)$. Since Algorithm 2 works on the premise of convergence of Algorithm 1, its complexity is negligible compared with the former.

3 Performance evaluation

In this section, simulation experiments are performed to evaluate the proposed algorithm. A cluster with one MEO satellite and three LEO satellites (named as LEO_1, LEO_2, LEO_3 respectively) is selected in this simulation. Considering a variety of scenes between LEO/MEO satellites, which could cover more typical motion scenes without loss of generality. On the other hand, the trajectory of $Path_3$ is not considered due to none of RVT referring to Eq. (7). So, three scenarios are defined as following.

Scene 1 Three LEO satellites approach MEO satellite, then leave the MEO satellite concurrently.

Scene 2 One LEO satellite approaches MEO satellite with other two LEO satellites leaving the MEO satellite.

Scene 3 Two LEO satellites approach MEO satellite with other one LEO satellite leaving the MEO satellite.

Let MT_1, MT_2 and MT_3 be consecutive motion trajectories of LEO_1, LEO_2, LEO_3 respectively.

From Eq. (7), it can be informed that, for the three scenarios, the consecutive motion trajectories satisfy:

$$\begin{cases} MT_1, MT_2, MT_3 \subseteq \{Path_1 \cup Path_2\} & \text{Scene 1} \\ MT_1 \subseteq \{Path_1\};\ MT_2, MT_3 \subseteq \{Path_2\} & \text{Scene 2} \\ MT_2, MT_3 \subseteq \{Path_1\};\ MT_1 \subseteq \{Path_2\} & \text{Scene 3} \end{cases} \tag{42}$$

It is noticeable that the different motion trajectories of LEO satellites could be mapped into different motion scenes, which could potentially expand to diverse scenes.

Since the proposed utility function based RVT for different scenes can universally apply to other power allocation algorithms that are also used to optimize utility, to compare the performance improvement of the game theory power allocation based RVT algorithm (abbreviated as R-GTA) proposed in this paper, two other traditional baseline algorithms are adopted, which are greedy power allocation based RVT algorithm (abbreviated as R-GA) and water-filling power allocation based RVT algorithm (abbreviated as R-WA).

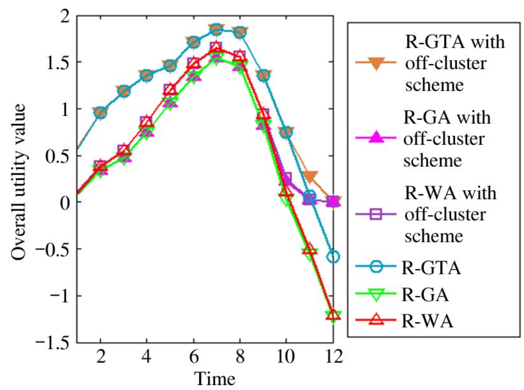
What's more, for the above three algorithms, both off-cluster schemes or not are separately employed to prove the validity of off-cluster schemes in diverse scenes.

The values of main parameters are shown in Table 1.

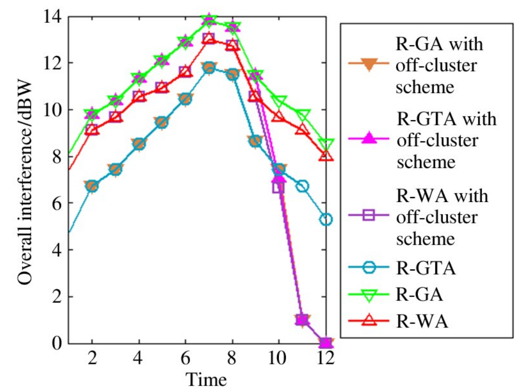
Table 1 Parameter configuration

Parameter	Value
The height of LEO_1 satellite	1110 km
The height of LEO_2 satellite	1200 km
The height of LEO_3 satellite	1325 km
The height of MEO satellite	7042 km
LEO satellite maximum transmission power	30 dBW
Threshold of interference power	15 dBW
Satellite center frequency	23 GHz
Bandwidth	500 MHz
Transmit/receive antenna gain	50 dB
Time guard interval	3 s
Data packet bits	20
Noise power	5×10^{-7} W
Satellite battery capacity	1.8×10^5 W · s

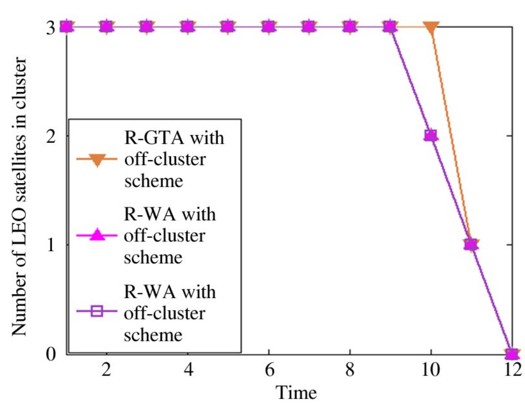
Overall, depicted in Fig. 2(a), Fig. 3(a) and Fig. 4(a), R-GTA outperforms other algorithms at the same condition with adopting off-cluster schemes or not respectively, R-WA has the second-best overall performance, while R-GA obtains the worst. For instance, in Fig. 2(a) at the sampling moment t_{12}, R-GTA has a 0.75 overall utility value gain compared with R-GA/R-WA. At the sampling moment t_1 shown in Fig. 3(a), R-GTA has a 0.4 and 0.2 gain paralleled with R-GA and R-WA respectively. Also, Fig. 4(a) presents that at the sampling moment t_6, R-GTA still surpasses R-GA and R-WA with 0.6 and 0.5 utility value respectively. The reason is that R-GTA implicates collaboration by the light of cost function, which could optimize the overall utility value through attaining Nash equilibrium. Even though R-GA maximizes the utility value of each participant without gambling, it ignores the interference caused by other participants making the overall interference power the largest, correspondingly the overall utility is not promising. The R-WA first obtains the 'water injection line' based on R-GA, and then allocates power resources according to the channel quality of each participant. It is known from water-filling theorem which allocates more (less) power resources to the participants with better (worse) channel conditions, so as to some degree, it will restrain the interference among participants. Therefore, the overall performance of R-WA is better than R-GA. Nevertheless, R-WA only depends on the 'water injection line', not taking all participants' impacts to the integrated performance into account, so its performance is poorer than R-GTA. Since the variation tendency of the overall interference power is identical to the variation tendency of the overall utility value, similarly it can be got that the overall interference power of R-GTA is also dominant to be the lowest shown in Fig. 2(b), Fig. 3(b), and Fig. 4(b). Like Fig. 3(b), the overall interference power of R-GTA is nearly 1 dBW/2 dBW less than R-WA/R-GA respectively, the reason is as discussed above.



(a) Change curve of overall utility value



(b) Change curve of overall interference



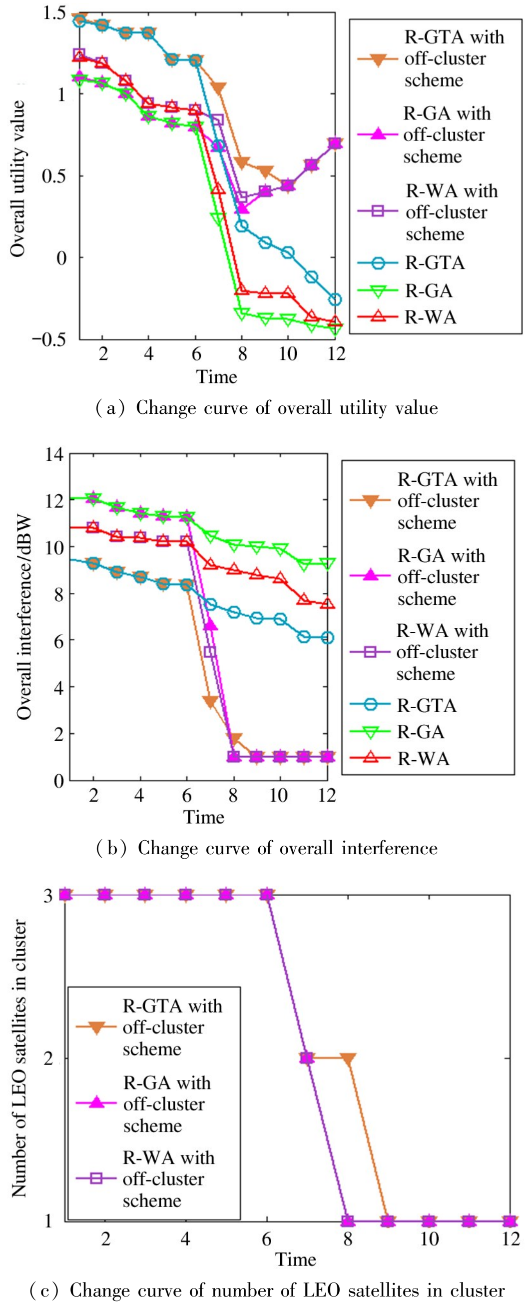
(c) Change curve of number of LEO satellites in cluster

Fig. 2 Performance comparison for different algorithms under Scene 1

In the case of Scene 1 as shown in Fig. 2(a), all LEO satellites approach to MEO satellite at the beginning. Subsequently, LEO-MEO inter-satellite links are shortening, while all LEO satellites' channel qualities are improving. So throughput can be mainly improved by increasing transmission power for each LEO satellite, which is positively correlated with the utility value. Hence the overall utility values of all algorithms are gradually increasing until reaching a distribution from 1.5 to 1.9. After that, three LEO satellites begin to direct away from MEO satellite simultaneously, the overall utility value becomes worse correspondingly like a reverse process. As time goes by, when the RVT of any specific satellite is insufficient to a certain degree, the utility will be punished with a large penalty of RVT, leading to the overall utility value plummeting further. Eventually, more LEO satellites are afflicted with severe penalties as time continues going, leading to the overall utilities for all algorithms degrading to a negative value from −1.25 to −0.5. By introducing the off-cluster scheme, LEO satellites whose utility values are below their thresholds will leave cluster, so the rate of decline for utility value has diminished. Finally, when all three satellites are off cluster, the utility value is 0. Since R-GTA with off-cluster scheme has a better performance than the other two with off-cluster schemes due to R-GTA with predominant performance as analysis before, at the sampling moment t_{10}, each participant's utility value of R-GTA with off-cluster scheme is still higher than the threshold. But at the same time for R-GA and R-WA with off-cluster schemes, there is both one participant's utility value lower than the threshold, contributing to one LEO satellite off cluster as shown in Fig. 2(c). Particularly, at the sampling moment t_{12}, for the same R-GTA, the overall utility value increases by 0.6 with off-cluster scheme; also for the poor performance of R-GA and R-WA, the improvement is even more promising. These results efficiently prove the better properties of R-GTA and off-cluster scheme. In a word, compared with the other two baseline algorithms, R-GTA with off-cluster scheme can not only ensure the overall utility value but also guarantee the number of activated LEO satellites in cluster, that is, to maximize the final value of LEO satellites with quite insufficient RVT as possible.

Fig. 2(b) shows that the overall interference power increases while three LEO satellites are approaching to MEO satellite due to the increasing transmission powers along with the better channel conditions. The maximal overall interference power is near 14 dBW for GA which is also under the threshold of interference power. After that, the overall interference power decreases with link distance increases similarly. When any LEO satellite is off cluster owing to utility value below threshold, such LEO satellite would not be assigned power resources from MEO satellite so that not causing any interference consequently, thus the overall interference power has a deeper plunge. Eventually, the interference power is 0 dBW in terms of all LEO satellites having been off cluster.

In Fig. 3(a) as the case of Scene 2, two LEO satellites' utility values are decreasing due to the two leaving away from MEO satellite, despite another satellite's utility value increasing in the meantime, the overall



(a) Change curve of overall utility value

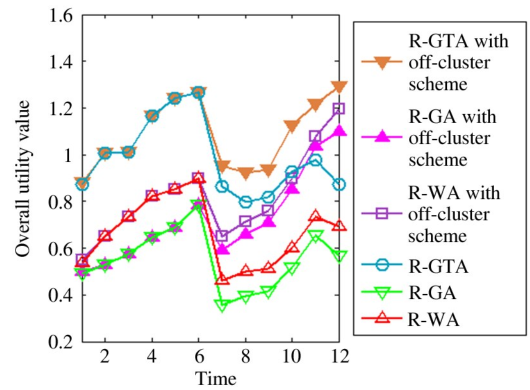
(b) Change curve of overall interference

(c) Change curve of number of LEO satellites in cluster

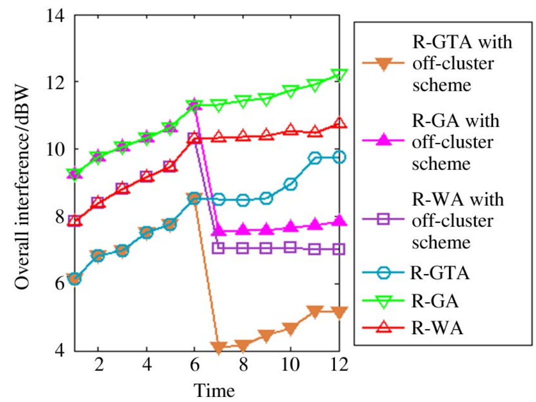
Fig. 3 Performance comparison for different algorithms under Scene 2 utility value is still decreasing over time. When the RVT of the two LEO satellites is much insufficient, they will be punished by the RVT cost function considerably, and the overall utility value decreases sharply. Adopting the off-cluster scheme, at the sampling moment t_7, one LEO satellite is off cluster for all algorithms as shown in Fig. 3(c). At the sampling moment t_8, due to the better performance of R-GTA than the other two, the remaining LEO satellites still keep in cluster for R-GTA with off-cluster scheme, but both R-GA and R-WA with off-cluster schemes have one more LEO satellite leaving cluster. The penalty of RVT increases along with time keeping on, finally all three algorithms have only one LEO satellite in cluster at the sampling moment t_9. By this time, there is only one LEO satellite staying in cluster with no gambling or re-allocation, so the performances of all algorithms are identical. The utility value increases from 0.4 to 0.7 as the last LEO satellite in cluster is approaching to MEO satellite. And compared with no off-cluster scheme at R-GTA in parallel, it improves from 0.3 to 1.

Fig. 3(b) gives the overall interference decreasing before any of LEO satellites leaving cluster referring to the identity trend for interference power and utility value as analysis above. At the sampling moment t_7, one LEO satellite is off-cluster in all employing off-cluster schemes algorithms. This satellite is not allocated power resource leading no interference to others, so the total interference greatly reduces. With time carrying on, one additional LEO satellite is off cluster again, thus the total interference further reduces. When only one LEO satellite remains in cluster at last in all three algorithms, since no interference is caused by other LEO satellites, the total interference barely leaves thermal noise which is equal to about 1 dBW in all algorithms.

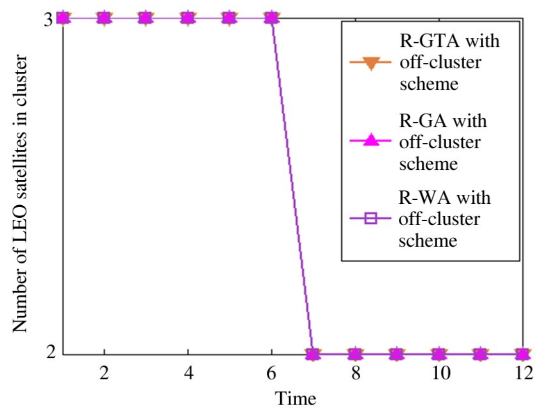
In Fig. 4(a) for the case of Scene 3, it can be observed that one LEO satellite's utility value is decreasing, while two are increasing, so the overall utility value is increasing over time. When the removed LEO satellite has quit far away from MEO satellite, which has left a lack of RVT, so there will be a great penalty by RVT cost function that the increasing trend has a big drop of about 0.4. At the sampling moment t_7, the only LEO satellite which has been seriously punished by the RVT cost function is off cluster as shown in Fig. 4(c), so the total utility value improves profoundly for all algorithms with employing off-cluster schemes. If the algorithm does not employ off-cluster scheme, the total utility value still increases in a certain period of time, since the penalty caused by the RVT cost function is compensated by the other two profiting satellites. But as the penalty of RVT still accelerates, at the sampling moment t_{12}, the increasing trend has finally stopped and the utility loss is near 0.1. In the meantime, the utility has a significant performance boost of about 0.5 with off-cluster scheme for all algorithms.



(a) Change curve of overall utility value



(b) Change curve of overall interference



(c) Change curve of number of LEO satellites in cluster

Fig. 4 Performance comparison for different algorithms under Scene 3

As presented in Fig. 4(b), similarly, the overall interference is almost on the rise, resulting from two LEO satellites approaching to MEO satellite. But this uptrend is not applied to the sampling moment t_7 at which there is an overall interference drop due to one satellite off cluster with adopting off-cluster scheme algorithm.

4 Conclusion

A power allocation method of inter-satellite links for diverse motion scenes is proposed. Firstly, the inter-satellite motion scene of LEO/MEO satellites is modeled, and the RVT of LEO satellites is proposed based on the inter-satellite link distance of LEO-MEO satellites. The non-convex optimization problem of maximizing the overall throughput in cluster is constructed. Then a reasonable utility function based on RVT is designed, and the existence of Nash equilibrium for the proposed utility function in game theory application scenario is proved. At the same time, an effective off-cluster scheme for each LEO satellite is devised, considering individual's throughput and energy consumption. Finally, compared with baseline algorithms, the proposed R-GTA is under numerical simulations in three different motion scenarios at the conditions of introducing an off-cluster scheme or not respectively. From the simulation results, it can be seen that the proposed algorithm achieves a state of optimal overall utility, on one hand, it can maximize the final value of LEO satellites with insufficient RVT; and on the other hand, it can avoid interference caused and resource waste for these LEO satellites with low utility.

References

[1] LIU J, DU X Q, CUI J H, et al. Task-oriented intelligent networking architecture for the Space-Air-Ground-Aqua integrated network[J]. IEEE Internet of Things Journal, 2020,7(6):5345-5358.

[2] XU K, QU Y, YANG K. A tutorial on the Internet of things: from a heterogeneous network integration perspective[J]. IEEE Network, 2016,30(2):102-108.

[3] SIA. State of the satellite industry report[R]. Washington: SIA, 2020.

[4] XU Y C, WANG Y, SUN R J, et al. Joint relay selection and power allocation for maximum energy efficiency in hybrid satellite-aerial-terrestrial systems[C]//The 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications. Valencia: IEEE, 2016:1-6.

[5] ARAVANIS A, SHANKAR B, ARAPOGLOU P D, et al. Power allocation in multibeam satellite systems: a two-stage multi-objective optimization[J]. IEEE Transactions on Wireless Communications, 2015,14(6):3171-3182.

[6] CHEN M L, CHAI R, CHEN Q B. Joint route selection and resource allocation algorithm for data relay satellite systems based on energy efficiency optimization[C]// 2019 11th International Conference on Wireless Communications and Signal Processing (WCSP). Xi'an: IEEE, 2019: 1-6.

[7] ZHANG H M, LI Q, ZHANG Y J, et al. Game theory based power allocation method for inter-satellite links in LEO/MEO two-layered satellite networks[C]// 2021 IEEE/CIC International Conference on Communications in China (ICCC). Xiamen: IEEE, 2021: 1-6.

[8] JIANG C X, ZHU X M. Reinforcement learning based capacity management in multi-layer satellite networks[J]. IEEE Transactions on Wireless Communications, 2020,19(7):4685-4699.

[9] WU Z F, JIN F L, LUO J X, et al. A graph-based satellite handover framework for LEO satellite communication networks[J]. IEEE Communications Letters, 2016, 20(8):1547-1550.

[10] MUSUMPUKA R, WALINGO T M, SMITH J M. Performance analysis of correlated handover service in LEO mobile satellite systems[J]. IEEE Communications Letters, 2016,20(11):2213-2216.

[11] FONTAN F P, VAZQUEZ-CASTRO M, CABADO C E, et al. Statistical modeling of the LMS channel[J]. IEEE Transactions on Vehicular Technology, 2001, 50(6): 1549-1567.

[12] NASSAR A, YILMAZ Y. Reinforcement learning for adaptive resource allocation in fog RAN for IoT with heterogeneous latency requirements[J]. IEEE Access, 2019, 7:128014-128025.

[13] WANG Q K, QIAO S. Study on incentive mechanism of knowledge sharing in supply chain based on evolutionary game theory[C]//2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). Bangkok: IEEE, 2018: 1780-1785.

[14] SHANG F J, NIU X Y, HE D X, et al. Resource allocation and admission control algorithm based on non-cooperation game in wireless mesh networks[J]. Computer Communications, 2020, 152:63-71.

[15] SU J T, YANG S S, XU H T, et al. A stackelberg differential game based bandwidth allocation in satellite communication network[J]. China Communications, 2018, 15(8): 205-214.

[16] FUGENBERG D, TIROLE J. Game theory[M]. Cambridge: The MIT Press, 1991.

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