A Computing Resource Pricing Strategy of Satellite-Earth Double Edge Computing System

Bo Wang(✉), XinYing Xie, and Dongyan Huang

Key Laboratory of Wideband Communication and Signal Processing, Guilin University of Electronic Technology, Guilin, China
glbluewind@126.com

Abstract. The visions of 6G can be effectively realized by Low Earth Orbit(LEO) satellite system equipped with Mobile Edge Computing (MEC) servers. To stimulate service provisioning by the Mobile Edge Computing Operator (MECO), it is essential to study a pricing strategy. In this paper, a profit maxmization muli-MECO computing resource pricing (PMMP) strategy based on Stackelberg game is proposed by a competitive environment. The offloading problem of the user equipment (UE) and the resource pricing problem of MECOs can be solved in the proposed strategy. Simulation results indicate that the proposed pricing strategy can maximize the revenue of MECOs and reduce UEs costs at the same time.

Keywords: LEO · MEC · Price strategy · Stackelberg game

1 Introduction

From the 1st Generation(1G) to the 5th Generation (5G), mobile communication system has developed rapidly, providing people with faster and more convenient services. The vision of the 6th Generation (6G) is a unified network to build a global smart connect, which will push the Internet of everything towards the Intelligent Connectivity.

According to International Telecommunication Union-Telecommunication Standardization (ITU-T) Workshop on Network 2030, one of the three goals of 6G is ManyNets. It is a heterogeneous converged network, including satellite networks, MEC, dense networks, and so on [1].

Satellite networks can effectively establish global communications, which makes up for the disadvantage of small range of ground network. Due to high-speed transmission and low latency, LEO satellite network is increasingly being valued by the industry [2].

Using computing resources at the edge of the network, MEC provide low latency sever to UE [3]. Integration of MEC and LEO satellite networks, constituting a Satellite-Earth double edge computing system that can effectively realize the visions of 6G.

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As providers of MEC services, MECO derive economic returns from the services. In the scenarios of multi-MECO providing services, it is a worthwhile problem to study pricing strategies that achieve the interests of each operator and provide better services.

Several papers have been done to study the problem of resource pricing. In [4], a scenario of competition between edge and remote cloud service providers(CSPs) is proposed, the pricing strategy of computing resources with the goal of maximizing the profit of edge cloud is designed. Deng et al. studied the influence of operator income and the number of satellites on the pricing strategy, and proposed a network data diversion pricing mechanism to maximize the revenue of operators [5]. The cooperation scenario between the satellite MECO and the base station MECO is established in [6], and a joint optimization method of UE task execution sequence and satellite resource allocation is proposed to maximize the profits of MECO. However, the research emphasis of [4,5] ignored considering the cost of UE, and do not study the impact of offloading decisions on UE costs as well as MECO revenue. And [6] consider two MECOs cooperation scenarios in the network. In reality, there is often a competitive relationship between MECOs.

Motivated by above discussions, it is considered that there is a competitive relationship between MECOs in a Satellite-Earth double edge computing system. In order to maximize the revenue of MECOs, a PMMP strategy is proposed. It is proposed that MECOs and UEs are regarded as Stackelberg game. For this game, the existence of Nash equilibrium is discussed by theoretical analysis, and a backward induction method based on particle swarm optimization (PSO) is proposed to solve the problem. Finally, the simulation results are given to verify the theoretical analysis and proved the superiority of the proposed strategy.

2 System Model

2.1 Network Model

The network model of the Satellite-Earth double edge system is shown in Fig. 1, which is represented by a LEO satellite (LEO), a base station (BS), and N UEs (including smartphones, IoT nodes) [7]. The set of UEs expressed as $C_N = \{1, 2, \cdots, N\}$.

Due to the limited communication capacity, the IoT nodes transmit the tasks to the satellite by the sink node. The communication link between UEs and the BS is in the C band, and the communication link between UEs and the LEO satellite is in the Ku band. The system adopts Orthogonal Frequency Division Multiple Access(OFDMA) [8].

Because the amount of data of the computing result is much smaller than the original data size, the delay and energy consumption are ignored in the stage of returning the computing result [9].

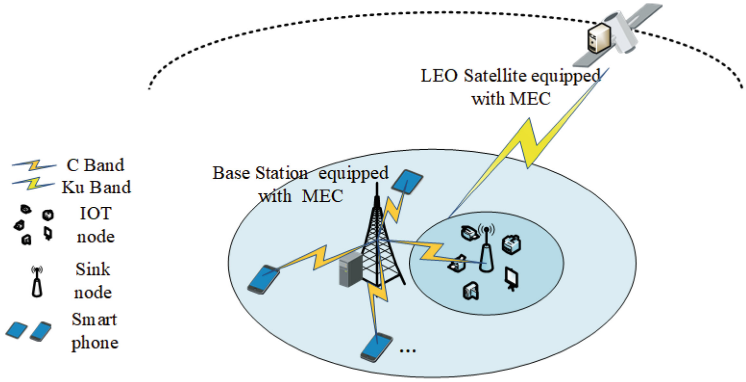


Fig. 1. Satellit-Earth double edge system architecture.

2.2 Computing Model

The offloading task parameter set of UE n is defined as $A_n = \{d_n, c_n, \lambda_n, l_n, k_n\}$, where d_n represents the data size of task (unit: bit). c_n (unit: $CPUcycles/bit$) is the calculation intensity and represents the number of CPU cycles needed to execute one bit of task.

Let $\lambda_n = \{0, 1\}$ stand for offloading decisions of UE n. The system adopts the way of partial offloading, part of the task can be completed locally, and the rest can be completed by MEC server. $\lambda_n = 0$ indicates that the task is offloading to the BS MECO, the offloading quantity is $l_n \in [0, d_n]$. $\lambda_n = 1$ indicates that the task is offloading to the LEO MECO, the offloading quantity is $k_n \in [0, d_n]$.

The BS Computing Model. The computing rate of the BS MEC are F_B (unit: $CPUcycles/s$), denote the computing rate allocated to UE n is $f_{B,n}$ (unit: $CPUcycles/s$), the computing delay of the UE n is

$$T_{B,n}^{com} = l_n c_n / f_{B,n} \tag{1}$$

And the transmission delay of UE n to the BS can be expressed as

$$T_{n,B}^{trans} = l_n / R_b^n \tag{2}$$

where R_b^n (unit: $bits/s$) represents the uplink transmission rate.

So the total execution delay of the UE n at the BS is given by

$$T_{n,B}^{exe} = T_{B,n}^{com} + T_{n,B}^{trans} \tag{3}$$

The energy consumption of the BS MEC server during processing the computing task n is defined as E_B^n , its expression is

$$E_B^n = P_B T_{B,n}^{com} = P_B l_n c_n / f_{B,n} \tag{4}$$

where P_B is the power of the BS MEC server.

The LEO Computing Model. The computing rate of the LEO MEC are defined as F_S (unit: $CPUcycles/s$), the computing rate allocated to UE n is $f_{S,n}$ (unit: $CPUcycles/s$). So the computing delay is

$$T_{S,n}^{com} = k_n c_n / f_{S,n} \tag{5}$$

The transmission delay of UE n to the LEO is given by

$$T_{n,S}^{trans} = k_n / R_S^n \tag{6}$$

where R_s^n (unit: $bits/s$) represents the uplink transmission rate.

Then the task propagation delay is

$$T_{n,S}^{pro} = 2D/c \tag{7}$$

where D is the linear distance between UE and the LEO, c is the speed of light.

So the total execution delay of the UE n calculated on the LEO is also expressed as

$$T_{n,S}^{exe} = T_{S,n}^{com} + T_{n,S}^{trans} + T_{n,S}^{pro} \tag{8}$$

The energy consumption of LEO during processing computing task n is defined as E_S^n, and its expression is

$$E_s^n = P_s T_{s,n}^{com} = P_s k_n c_n / f_{s,n} \tag{9}$$

where P_S is the power of the satellite MEC server.

3 Problem Formulation and The Proposed PMMP Strategy

3.1 Problem Formulation

MECO needs to set a unit price for computing resources, and UE needs to select and determine resource requirements.

The LEO MECO Utility Function. Define the LEO MECO utility function as U_{MEC}^S, which consists mainly of the resource cost paid by UE and its own loss cost, and express it as

$$U_{MEC}^S = \sum_{n=1}^{N_2} \left(p_n^S k_n c_n - \omega_2 P_S k_n c_n / F_{S,n} \right) \tag{10}$$

where ω_2 representing the unit price of energy consumption by the LEO MECO. Then its optimization problem is defiened by

$$\begin{aligned} &\max U_{MEC}^B (p_n^B, l_n) \\ &s.t.\, p_n^B \geq 0 \\ &\qquad l_n \geq 0 \end{aligned} \tag{11}$$

UE Utility Function. Definition the UE n utility function is U_n, which consists of two components: the execution delay and the cost to be paid for UE offloading. It has the form

$$U_n = \begin{cases} \beta_n T_{n,B}^{exe} + (1-\beta_n)(p_n^B l_n c_n - R l_n / \sum_{i=1}^{N} l_i), \lambda_n = 0 \\ \beta_n T_{n,S}^{exe} + (1-\beta_n)(p_n^S k_n c_n - R k_n / \sum_{i=1}^{N} k_i), \lambda_n = 1 \end{cases} \tag{12}$$

where R represents the reward of the MECO for UE's offloading, which is used to encourage offloading, and $\beta_n \in [0,1]$ represents the delay cost weight of UE n , $(1-\beta_n)$ represents the payment cost weight factor.

The optimization problem can be described by

$$\begin{aligned} &\min U_n \left(p_n^B, l_n, p_n^S, k_n\right) \\ &s.t.\, p_n^B \geq 0 \\ &\quad p_n^S \geq 0 \\ &\quad l_n \geq 0 \\ &\quad k_n \geq 0 \end{aligned} \tag{13}$$

The BS MECO Utility Function. The BS MECO utility function is defined as U_{MEC}^B, which is also composed of the resource fee paid by UE and its own loss cost like the satellite MECO utility function. The specific expression can be

$$U_{MEC}^B = \sum_{n=1}^{N_1} (p_n^B l_n c_n - \omega_1 P_B l_n c_n / F_{B,n}) \tag{14}$$

where ω_1 represents the unit energy consumption pice by the BS MECO.

The optimization problem is given by

$$\begin{aligned} &max\, U_{MEC}^B(p_n^B, l_n) \\ &s.t.\, p_n^B \geq 0 \\ &\quad l_n \geq 0 \end{aligned} \tag{15}$$

3.2 The Profit Maxmization Muli-MECO Pricing Strategy

The PMMP strategy in this paper divides the above problem into two sub-problems to solve. The first sub-problem is the offloading decision problem of UE. It is proposed that the offloading decision is made depending on the minimum cost criterion, and the MECO with lower cost is selected for offloading. The second sub-problem is the offloading quantity of UE and the resource pricing of MECO, which is established as a Stackelberg game, and the Nash equilibrium is solved by the backward induction method to get the optimal offloading quantity of UE and the optimal resource pricing of MECO.

The PMMP strategy flow chart is shown in Fig. 2. The specific process is as follows:

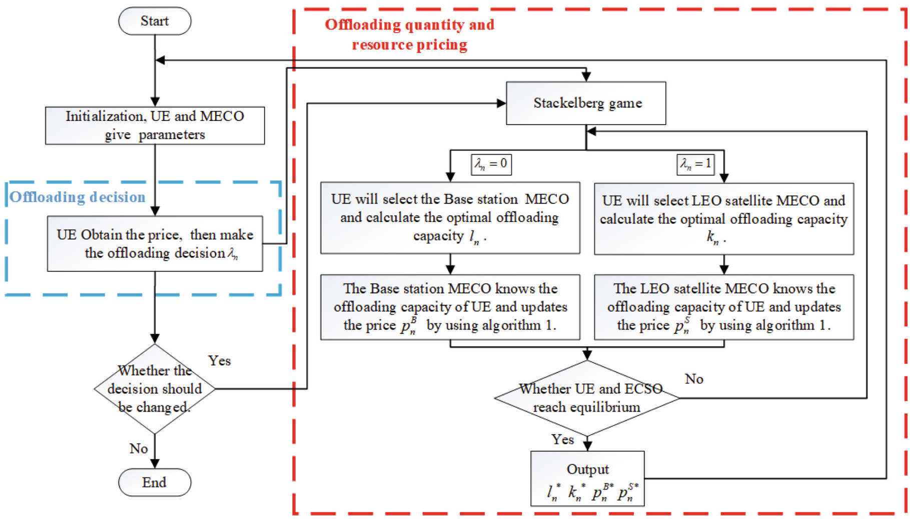


Fig. 2. Flowchart of the PMMP strategy.

Step 1: According to the minimum cost criterion, UE selects the BS MECO or the LEO MECO to offload the task.

Step 2: The optimal offloading quantity l_n^*/k_n^* of UE at this time is obtained by using the first derivative of UE utility function as 0.

Step 3: The offloading quantity received by the BS MECO or the LEO MECO determines the resource price respectively.

Step 4: Determine whether the Nash equilibrium is reached, if not, return to step 2; otherwise proceed to the next step.

Step 5: UE recalculates the cost to make a offloading decision, and if the decision changes, return to step 1; otherwise, it ends.

3.3 Offloading Decision

Considering the difference of computing power and performance between the BS MECO and the LEO MECO, the offloading decision problem of UE is studied.

When the UE n is offloading to the BS MECO, the cost function is assumed to

$$Z_{n,B} = \eta_n T_{n,B}^{exe} + (1 - \eta_n)(p_n^B l_n c_n) \tag{16}$$

where $\eta_n \in [0, 1]$ represents the delay weight factor of UE n, $(1 - \eta_n)$ represents the energy consumption weight factor.

When the UE n is offloading to the LEO MECO, the cost function is expressed as

$$Z_{n,S} = \eta_n T_{n,S}^{exe} + (1 - \eta_n)(p_n^S k_n c_n) \tag{17}$$

Each UE is selfish and wants to minimize its own cost, so the selection criterion for

$$\lambda_n = \begin{cases} 0, Z_{n,B} \leq Z_{n,S} \\ 1, Z_{n,B} > Z_{n,S} \end{cases} \tag{18}$$

3.4 Offloading Quantity and Resource Pricing

The pricing model based on Stackelberg game is shown in Fig. 3. Taking the BS MECO as the leader, the LEO MECO as the sub-leader, UE is the follower.

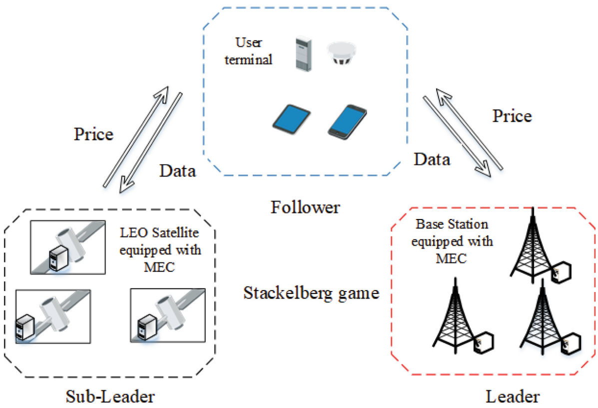


Fig. 3. The pricing model based on Stackelberg Game.

Nash Equilibrium. As mentioned above, formulate a three-layer Stackelberg game model. This game model is solved to obtain a Nash equilibrium in which the participant gets the value of the optimal function and the policy. In Nash equilibrium, the utility function does not change and therefore there is no incentive to change the policy [10]. We define the Nash equilibrium as follows.

Theorem 1. *Suppose and $p_n^{B^*}$,$p_n^{S^*}$ and l_n^*,k_n^* is the optimal resource price of the MECO and the optimal offloading quantity of UE n. When it meets the following conditions, it is the Nash balance point.*

$$U_{MEC}^{S^*}(p_n^*, k_n^*) \geq U_{MEC}^{S}(p_n^{S}, k_n^*) \tag{19}$$

And

$$U_n(p_n^{B^*}, l_n^*, p_n^{s^*}, k_n^* \geq U_n(p_n^{B^*}, l_n, p_n^{S^*}, k_n) \tag{20}$$

As well as

$$U_{MEC}^{B}(p_n^{B^*}, l_n^*) \geq U_{MEC}^{B}(p_n^{B}, l_n^*) \tag{21}$$

Proof. The utility function $U_n(p_n^B, l_n^s, p_n^S, k_n)$ of UE n is continuous on its offloading decision space set $\{l_n, k_n\}$, and then proves the unevenness of the utility function. When $\lambda_n = 0$, The effective function $U_n(p_n^B, l_n^s, p_n^S, k_n)$ finds the number of guidance in first guidance

$$\frac{\partial U_n}{\partial l_n} = \beta_n\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n^B}\right) + (1-\beta_n)\left(p_n^B c_n - R\frac{\sum\limits_{i=1 i\neq n}^{N} l_i}{\sum\limits_{i=1}^{N} {l_i}^2}\right) \tag{22}$$

The number of first-order guidance is equal to 0, the l_n^* obtained as

$$l_n^* = \sqrt{\frac{R\sum\limits_{i=1 i\neq n}^{N} l_i}{p_n^B c_n + \frac{\beta_n}{1-\beta_n}\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n}\right)}} - \sum_{i=1, i\neq n}^{N} l_i \tag{23}$$

Then, the effective function finds the number of guidance in second derivative guidance

$$\frac{\partial^2 U_n}{\partial {l_n}^2} = (1-\beta_n)R\frac{2\sum\limits_{i=1, i\neq n}^{N} l_i}{\left(\sum\limits_{i=1}^{N} l_i\right)^3} \tag{24}$$

Because $\beta_n \in (0, 1)$, and R are positive numbers, it is clear that the second -order derivative of UE utility is positive. So it is a rigorous convex function, and l_n^* is the minimum value point. In the same way, when $\lambda_n = 1$, it can be proved that U_n is also a strict convex function for k_n.

Substitute l_n^* into the utility function U_{MEC}^B, and find the second derivatives with respect to p_n^B, and derive the expression

$$\begin{aligned} \frac{\partial^2 U_{MEC}^B}{\partial (p_n^B)^2} &= -c_n^2 \frac{\left(R\sum\limits_{i=1 i\neq n}^{N} l_i\right)^{\frac{1}{2}}}{\left(p_n^B c_n + \frac{\beta_n}{1-\beta_n}\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n}\right)\right)^{\frac{3}{2}}} \\ &+ \left(p_n^B - \frac{\omega_1 P_B}{F_{B,n}}\right)\left(\frac{3}{4}\frac{c_n^3\left(R\sum\limits_{i=1 i\neq n}^{N} l_i\right)^{\frac{1}{2}}}{\left(p_n^B c_n + \frac{\beta_n}{1-\beta_n}\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n}\right)\right)^{\frac{5}{2}}}\right) \end{aligned} \tag{25}$$

$$\frac{\partial^2 U_{MEC}^B}{\partial (p_n^B)^2} + \frac{\beta_n}{1-\beta_n}\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n}\right)\left(\frac{3}{4}\frac{c_n^3\left(R\sum\limits_{i=1 i\neq n}^{N} l_i\right)^{\frac{1}{2}}}{\left(p_n^B c_n + \frac{\beta_n}{1-\beta_n}\left(\frac{c_n}{F_{B,n}} + \frac{1}{r_n}\right)\right)^{\frac{5}{2}}}\right) = -\frac{1}{4}c_n^2\frac{(RB)^{\frac{1}{2}}}{A^{\frac{3}{2}}} - \frac{\omega_1 P_B c_n^3}{F_{B,n}}\frac{(RB)^{\frac{1}{2}}}{A^{\frac{5}{2}}} < 0 \tag{26}$$

Obviously, $\frac{\partial^2 U_{MEC}^B}{\partial (p_n^B)^2} < 0$ is always true, so U_{MEC}^B is a concave function and there is a maximum value. Therefore, it is proved that the Nash equilibrium of Stackelberg game exists and is unique. Substituting k_n^* into U_{MEC}^S , it is proved that U_{MEC}^S is also a concave function. □

PSO Algorithm for Solving Nash Equilibrium. As mentioned above, the existence of the Nash equilibrium solution of the game is proved, and the proposed game is solved by the backward induction method [11]. A pricing strategy for the BS MECO and the LEO MECO using PSO algorithm is proposed [12], as shown in algorithm 1.

Algorithm 1. Particle Swarm Optimization (PSO) algorithm

Initialize particle swarm parameters
for each particle i **do**
  for each dimension d **do**
    Initialize position x and velocity v randomly within permissible range
  end for
end for
Iteration $k = 1$
while $k < K$ **do**
  for each particle i **do**
    Calculate fiteness value
    if the fitness value is better than p in history **then**
      Set current fitness value as the p
    end if
  end for
  Choose the best fitness value of the particle as the p
  for each particle i **do**
    for each dimension d **do**
      Calculate velocity by $v_i^d = wv_i^{d-1} + c_1 r_1(pbest_i^d - x_i^d) + c_2 r_2(gbest^d - x_i^d)$
      Update particle position by $x_i^{d+1} = x_i^d + v_i^d$
    end for
  end for
  $k = k + 1$ and $p_n^B, p_n^S \leftarrow (x_{pbest}^1, x_{pbest}^2)$
end while
return p_n^B, p_n^S

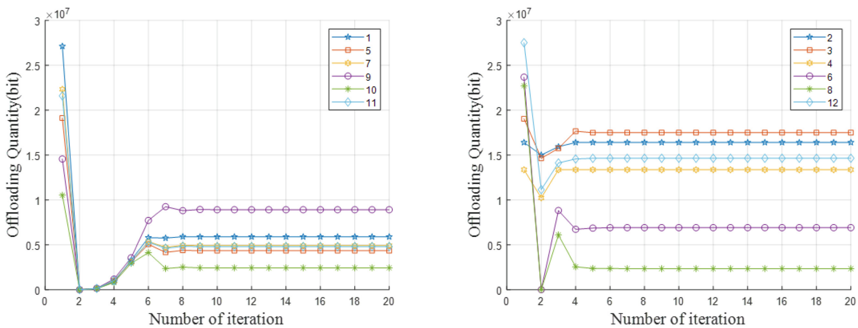
4 Simulation Results and Analysis

4.1 Simulation Parameters Setting

Simulation parameters are showed in Table 1 [13,14]. The altitude of LEO is 500km, the number of UE is $N = 12$. Set the uplink transmission rate of UE for the LEO MECO and the BS MECO are different, which are 200Mbps and 100Mbps respectively.

Table 1. Simulation parameters [13,14]

Parameter	value of LEO	value of BS
Computing rate of MEC	54Gcycles/s	42Gcycles/s
Uplink transmission rate	200Mbps	100Mbps
Charge factor for initial task computing	0.06$/Megacycle	0.04$/Megacycle
Server power	400W	600W
LEO Ku frequency band	12-18GHz	
Task computing intensity	[500,1500]cycle/bit	
Task size	[1,3]MB	
Reward of the MECO R	600	
The altitude of LEO	500km	
The number of UE	12	

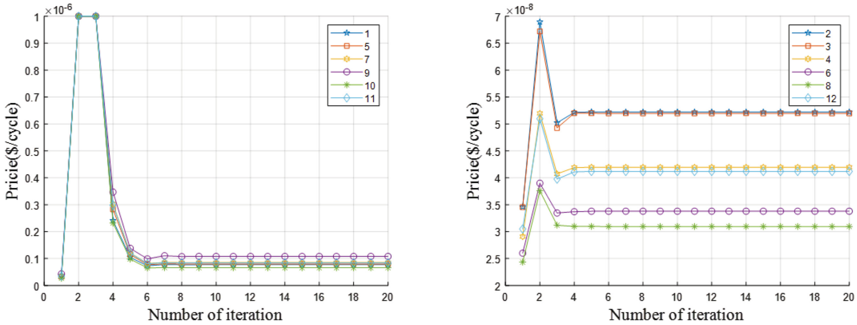


(a) LEO-MEC offloading iteration process (b) BS-MEC offloading iteration process

Fig. 4. Offloading quantity iteration process.

4.2 Result Analysis

Figure 4 shows the offloading quantity and the offloading decision of UE with iteration process. Fig. 4 (a) shows that UE 1,5,7,9,10,11 are offloading to LEO-MEC, (b) shows that UE 2,3,4,6,8,12 are offloading to BS-MEC. There is a common trend, it can be seen that as the number of iterations increases, the offloading quantity of UEs after the seven iterations process, reaching the Nash equilibrium of the game. Each UE converges to its respective optimal offloading quantity.



(a) LEO-MEC price iteration process (b) BS-MEC price iteration process

Fig. 5. Price iteration process.

Figure 5 shows the computing resource price iteration process by two MECOs. Figure 5(a) show pricing process by LEO MECO, and (b) show pricing process by BS MECO. It can be seen that with the increase of the number of iterations, the price of the MECO tends to stabilize after about the seven iterations process, reaching the Nash equilibrium of the game, and the MECO sets different resource prices according to the amount of offloading quantity by UE.

Figure 6 shows the relationship between MECO's price and UE's offloading quantity. In the iterative process, when the resource price gradually decreases, the offloading quantity of UE increases gradually. When the resource price increases gradually, the offloading quantity of UE begins to decrease. And because there is a Nash equilibrium in the game, it can be seen that the decisions of the game participants do not change after seven iterations, it is consistent with the definition of Nash equilibrium.

Figure 7 plots the utility function values of UE and MECO by different strategies. The three strategies in the figure are the PMMP strategy, the flat price strategy and the flat offloading ratio strategy. The flat price strategy means that MECO sets the resource price to a fixed value, the offloading quantity of UE with the best utility according to the price choice. The flat offloading ratio strategy means that the offloading ratio of UE is keeping a fixed value of 0.5, the resource price is adjusted to the optimal price by MECO.

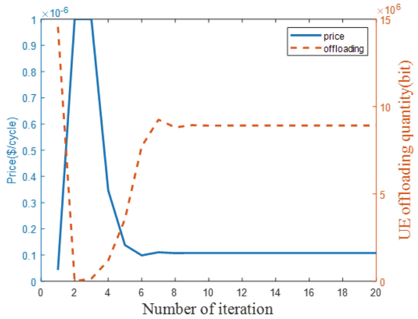


Fig. 6. Pricing vs. UE offloading quantity.

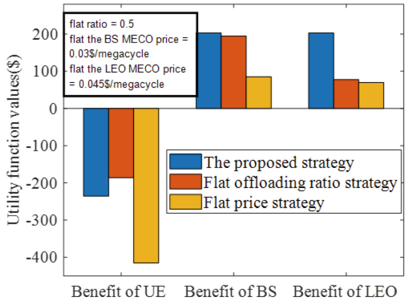


Fig. 7. Utility function values by different strategies.

The results show that in terms of the utility of MECO, the PMMP strategy is better than other strategies, especially the flat price strategy, because the price is set low, UE will offload a large number of task data to MECO, resulting in MECO lose more revenue. Compared with the flat offloading ratio strategy, the proposed strategy can increase the overall revenue of MECO to 50% and guarantee a reduction of about 26% in UE costs.

4.3 Complexity Analysis

The complexity comparison of three strategies mentioned above is showed in Table 2, M represents the maximum number of iterations of PSO algorithm.

The worst-case time complexity of the PMMP strategy can be calculated as follow: the optimal solution of the function cannot be found until the iteration number reaches its maximum, then the time complexity of overall strategy is $\mathrm{O}(3N + 4N^2 + N^2(N + M^2))$.

Table 2. Complexity comparison

Performance Parameter	PMMP strategy	Flat offloading quantity strategy	Flat price strategy
time complexity	$\mathrm{O}(3N + 4N^2 + N^2(N + M^2))$	$\mathrm{O}(3N + 4N^2 + N(N + M^2))$	$\mathrm{O}(3N + 3N^2)$

5 Conclusion

In this paper, a computing resource pricing strategy based on Stackelberg game of Satellite-Earth double edge computing system is proposed. The existence of Nash equilibrium of the game is proved theoretically. And the solution of Nash equilibrium is obtained by using the backward induction method based on PSO algorithm. It is proved that the proposed strategy can maximize the revenue of MECOs while reducing the cost of UEs.

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