Edge Cache Resource Allocation Strategy with Incentive Mechanism

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Abstract. Edge computing technology can effectively alleviate the problems of network congestion and poor user experience quality in current mobile social networks. In this paper, an edge cache resource allocation strategy for mobile social networks based on incentive mechanism is presented. The incentive cache model is modeled as a Stackelberg game, and the utility functions of the macro base station and the social interest group are constructed respectively. The optimal unit cache resource price strategy for the macro base station and the optimal cache resource demand strategy for the social interest groups are obtained by using distributed iterative algorithm. The results show that the proposed mechanism has lower average content transmission delay and higher user experience quality.

Keywords: Mobile social network · Edge computing · Incentive mechanism · Cache allocation

1 Research Background

The introduction of edge cache [1, 2] technology into mobile social network [3] can effectively alleviate the network congestion and poor user experience quality in current mobile social networks [4]. Given the above problems, domestic and foreign researchers have carried out extensive and in-depth research. To improve the utilization rate of resources and the network capacity, literature [5] proposed a caching scheme with social awareness and payment incentives. Data caching was modeled as a socially aware payment game to motivate end users to cache content for other end users, and the cost function was constructed using social relation to minimize the cost of network access to content. To encourage users to share cached resources and improve the social welfare of cellular networks, literature [6] proposed a D2D caching strategy with joint incentive scheme, categorizing users according to their preference. The base station gave users incentives based on the size of cache resources shared by users, and contract theory was used to build optimization problems to motivate users to share cache resources and maximize base station utility. However, the literature [5] and [6] only considered motivating users to participate in content caching to allocate their cache resources, but not considering to

J. Xiong et al. (Eds.): MobiMedia 2021, LNICST 394, pp. 224–237, 2021.
https://doi.org/10.1007/978-3-030-89814-4_17

encourage selfish base stations to participate in content caching. Literature [7] proposed a cache resource allocation strategy to motivate selfish base stations to participate in content caching. The content server used the cache resources of the base station to provide services to users. The base station makes profits by renting cache resources to the content server, and the interaction between the base station and multiple content service providers is modeled as a Stackelberg game to maximize the utility of the base station and the content server ultimately. Literature [8] put forward an edge cache incentive mechanism based on contract theory. The Internet service providers rented out their resources to content service providers for profit, and the content server cached its most popular content in the rented base station to provide better service to users. Considering the different demands of users for service quality, the incentive mechanism is designed based on contract theory to maximize the utility of Internet service providers. The literature [7] and [8] only considered motivating selfish base stations to participate in content caching, but not considering motivating selfish users to participate in content caching. At present, there are few documents that simultaneously encourage selfish users and selfish base stations to participate in content caching.

Therefore, this paper proposes a mobile social network edge cache resource allocation strategy based on incentive mechanism. The macro base station gives corresponding incentives based on the contribution of social interest groups to cache process. Social interest groups pay incentives to base stations according to the number of cache resources given by base stations. The interaction between the macro base station and the social interest groups is modeled as a Stackelberg game problem, and the utility functions of macro base station and social interest groups are constructed based on unit cache resource price, cache resource demand, the contribution of social interest group. Using distributed iteration method, the optimal unit cache resource price of macro base station and the optimal cache resource demand of social interest groups are obtained.

2 System Model

2.1 Network Model

Consider a cellular network scenario in which all small base stations and end users in a macro base station have caching capabilities. The network is mainly composed of content servers, macro base stations, small base stations, and end users, as shown in Fig. 1.

Content Server: stores all the content that the user needs, but is far away from the end user. When the end user acquires the content from the content server, it will produce a long delay, which will lead to poor user experience quality.

Small base station: as an edge cache node, under the control of the macro base station, the content is cached for users who purchased its cache resources. Assuming that the coverage radius of the micro base station is r_s, it follows a homogeneous Poisson process with an intensity of λ_s in space [9], and the intensity λ_s represents the number of micro base stations per unit area. All micro base stations within the coverage of the macro base station have the same storage capacity, and the amount of content cached for each social interest group is at most C_{sn}.

End user: both as edge cache nodes and as content requestors. Assuming that the D2D communication radius of the end user is r_u, it follows a homogeneous Poisson process with an intensity of λ_u in space, the intensity of λ_u represents the number of end users in a unit area, and the maximum number of content cached for each social interest group is C_n. $N = \{1, \ldots, i, \ldots, N\}$ represents all social interest groups within the coverage of the macro base station.

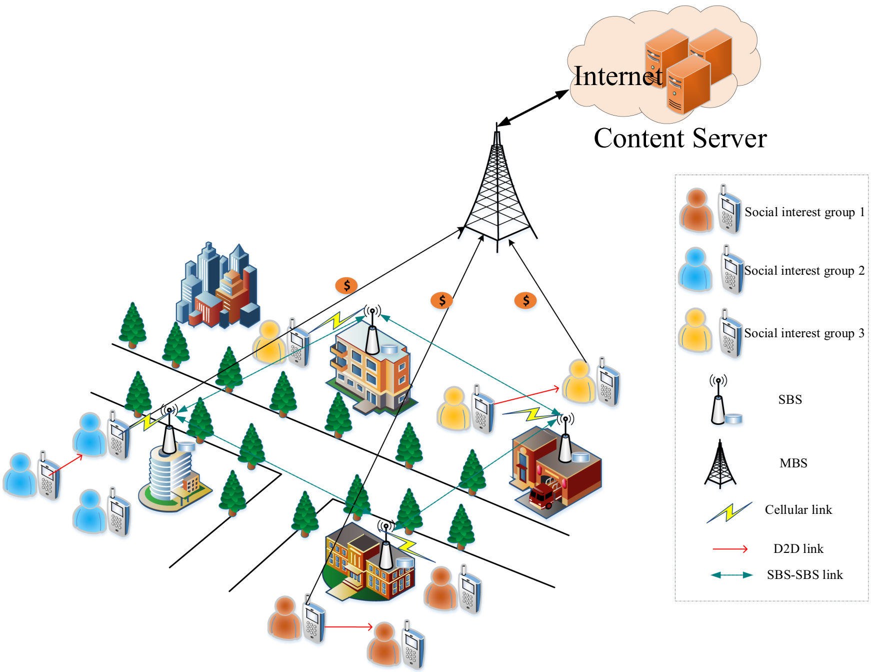

Fig. 1. Network model

In this cellular scenario, users can obtain the content in one of the following ways:

1. If the requested content is found in an adjacent end user, the user will first retrieve the requested content from the adjacent end user through the D2D link. And assume that the delay in retrieving content from adjacent end users is d_{D2D}.
2. If the content requested by the user cannot be found in an adjacent end user, the user obtains the requested content from the connected small base station through a cellular link. It is assumed that the delay of obtaining content from the micro-base station is d_{SBS}.
3. If the content requested by the user cannot be found in the connected small base station, the user obtains the requested content from the adjacent small base station through the connected small base station. It is assumed that the delay of obtaining content from the adjacent small base station is also d_{SBS}.
4. If the user cannot obtain the requested content through the above three methods, the user obtains the requested content from the content server through the connected

small base station. And assume that the delay in retrieving content from the content server is d.

2.2 Incentive Mechanism Model

When a large number of users at the same time obtain content from the base station, easy to cause network congestion, to alleviate the network congestion, the base station will encourage users to participate in content caching and sharing, according to the user to ease network congestion of interest groups in social contribution to give different incentives, improving user participation in mobile social network content caching and share the enthusiasm. The contribution of a social interest group can be measured by the number of shared cache resources provided by users in the group and the activity of users. The more shared cache resources, the greater the amount of cached content, the higher the activity of users, the higher the probability of meeting other users, and the higher the probability of successful content sharing. If Acer stands within range of the number of users with Shared cache resources for Q_u, according to the Shared cache resources in social interest group n provide Q_u and all users in the group's average active $\overline{V_n}$, determine the contribution of social interest group n, and do the normalized processing, the resulting social interest group contribution dg_n of n are as follows:

$$dg_n = \frac{2}{\pi} \arctan(\frac{Q_n}{Q_u} + \overline{V}_n) \tag{1}$$

2.3 Encounter Probability and Content Request Probability Model

The cache location includes the micro-base station and the end user within the coverage range of the Acer Station. The cache resources of all micro-base stations and the end user are managed by the Acer Station. The total cache resources managed by the Acer Station is Q, where $Q = Q_s + Q_u$. Each social interest groups based on their needs, and the utility macro base station stood to determine their cache resource demand, let $s = \{s_1, s_2, \cdots, s_n\}$ said Acer stand all social interest groups within a range of the cache capacity requirements of combination, where $0 \leq s_n \leq Q$ and $s_n = s_{sn} + s_{un}$, $s_{sn} = \alpha s_n$ said cache capacity, from the small base station, $s_{un} = (1 - \alpha)s_n$ said the cache capacity from the adjacent user equipment. Assuming that the social interest group rents the small base station in the Acer station cell with the same probability, the micro-base station rented by the social interest group n can be modeled as a sparse homogeneous Poisson process of intensity $\lambda_s s_{sn}$, then the probability of users in the social interest group n within the coverage range of their rented small base station can be expressed as:

$$p_{ns} = 1 - \exp(-\lambda_s s_{sn} \pi r_s^2) \tag{2}$$

Similarly, the end users rented by the social interest group n can be modeled as a sparse homogeneous Poisson process of intensity $\lambda_u s_{un}$, and the probability of users in the social interest group n meeting their leased end users can be expressed as

$$p_{ns} = 1 - \exp(-\lambda_s s_{sn} \pi r_s^2) \tag{3}$$

Within different social interest groups, users will request different kinds of content and the popularity of their content will vary. Assumptions in the social interest group n, the user sets the contents of the request $F = \{F_1, F_2 \cdots F_m\}$, and assuming that each content of the same size. The content sets requested by users in the social interest group are arranged in descending order of popularity. The higher the popularity of the content at the top, that is, the content F_1 has the highest popularity, while content F_m has the lowest popularity. Users will request content F_f in the content set independently with probability, and it is assumed that $p_{n,f}$ follows the Zipf distribution with parameter γ [10]. That is:

$$p_{n,f} = \frac{f^{-\gamma}}{\sum_{i=1}^{m} i^{-\gamma}}, f = 1, 2, \cdots, m. \tag{4}$$

Where γ represents the content popularity parameter in the social interest group n.

3 Cache Resource Allocation Policy

In this part, we first model the cache resource allocation problem of the macro base station as a Stackelberg game model, then use the distributed iteration method to obtain the optimal unit cache resource price of the macro base station and the optimal cache resource demand of the social interest group, and finally get the edge cache resource allocation algorithm based on the incentive mechanism.

3.1 Stackelberg Game Model

The interaction between the macro base station and the social interest group during the allocation of the macro base station cache resources conforms to the relationship commonly used between two conflicting entities in game theory. Specifically, in the mobile social network, the interaction relationship between the macro base station and the social interest group conforms to the hierarchical relationship in the Stackelberg game, and there are two types of participants in this model: leaders and followers [11].

Leader: In this game model, the macro base station is regarded as the leader, and the leader is responsible for the pricing strategy of the cache resources it manages. Leaders can satisfy the needs of users in social interest groups by providing cache resources to social interest groups. At the same time, leaders can influence the demand of cache resources of social interest groups through pricing strategies to maximize their own utility.

Followers: Treat each social interest group as a follower. Followers will adjust their caching resource demand strategy according to the price of caching resource set by the leader and the total utility obtained by users in the social interest group.

Policy: For macro base station, the policy is to publish the price p per unit cache resource. For the social interest group, the strategy is to formulate the cache resource demand strategy $s = \{s_1, s_2, \cdots, s_n\}$, where s_n represents the size of the cache space purchased by the interest community n at the macro base station, and it satisfies $0 \leq s_n \leq Q$. The size of cache space purchased by all social interest groups on the macro base station should meet $\sum_{n=1}^{N} s_n \leq Q$.

The game between the macro base station and the Social Interest Group is divided into two stages. In the first stage, the macro base station first develops the unit cache resource price strategy p, and publishes this price strategy to all social interest groups. The social interest groups determine their own cache resource demand strategy s according to the received price strategy. In the second stage, after the macro base station learns the caching resource demand strategy of the social interest group, it readjusts the pricing strategy to maximize its utility.

3.2 The Utility Function

For the macro base station and the Social Interest Group, the utility function reflects the players' satisfaction with their choice of strategy. The proof of the existence of Nash equilibrium points can show that the non-cooperative game between social interest groups can reach Nash equilibrium, and any social interest groups will not gain if they want to change their own strategies.

1. Social interest group utility function

Social interest group utility function according to the definition of social interest groups, social interest groups in the same user will be asked to similar content and is willing to share the social interest groups to buy cache resource cost, namely the social interest group of the utility function for the effectiveness of its end users in the group, the sum of its utility function through the benefits and costs of two parts, the utility function U_n of social interest group n can be expressed as:

$$U_n = R_n(s_n) - C_n(s_n) \tag{5}$$

Where $R_n(s_n)$ and $C_n(s_n)$ represent the benefits and expenses of the social interest group respectively.

The content access delay of social interest group n is related to the size of leased cache resources s_n, which is an increase function of s_n. The incentive that social interest group n receives from the base station is related to its contribution degree dg_n. The higher the contribution degree, the more incentive it receives. Then, the income function $R_n(s_n)$ of social interest group n can be expressed as:

$$\begin{aligned} R_n(s_n) = \eta_1 \cdot (d - d_{SBS}) \cdot p_{ns} \cdot \sum\nolimits_{f=1}^{C_{sn}} p_{n,f} + dg_n p_1 \\ + \eta_1 \cdot (d - d_{D2D}) \cdot p_{nu} \cdot \sum\nolimits_{f=C_{sn}+1}^{C_n} p_{n,f} \end{aligned} \tag{6}$$

Where η_1 represents the revenue factor of delay saving, p_1 represents the unit contribution cost of the base station to the social interest group, $d - d_{SBS}$ represents the delay saving of acquiring content from the small base station, and $d - d_{D2D}$ represents the delay saving of acquiring content from adjacent end users.

For the social interest group n, its cost is the cost that the social interest group uses to motivate the base station to give cache resources, then the cost function $C_n(s_n)$ of the social interest group n can be expressed as:

$$C_n(s_n) = ps_n \tag{7}$$

Based on the benefit function and cost function of social interest group, the utility function U_n of social interest group n is finally obtained as follows:

$$U_n = \eta_1 \cdot (d - d_{SBS}) \cdot p_{ns} \cdot \sum_{f=1}^{C_{sn}} p_{n,f} + dg_n p_1 - ps_n + \eta_1 \cdot (d - d_{D2D}) \cdot p_{nu} \cdot \sum_{f=C_{sn}+1}^{C_n} p_{n,f} \quad (8)$$

According to the price strategy p of the current macro base station, each social interest group n adjusts its own cache resource demand strategy s_n and finally achieves the optimal cache resource demand strategy s_n^*. By maximizing its own utility function, the optimal cache resource demand strategy s_n^* can be obtained as follows:

$$s_n^* = \arg\ \max U_n(p^*, s_n, s_{-n}^*) \quad (9)$$

Where p^* represents the optimal price strategy selected by the macro base station, s_{-n}^* represents the optimal cache resource demand strategy selected by other social interest groups.

2. The utility function of macro base station

The macro base station needs to build and maintain the caching capability of the edge nodes, so the caching service provided for the social interest group is not free, and the cost is compensated by the incentives given by the social interest group. The utility function of the macro base station can be expressed as:

$$U_0 = R(p) - C(s) \quad (10)$$

Where $R(p)$ and $C(s)$ respectively represent the revenue and expense of the macro base station.

The revenue of the macro base station is the incentive fee given to it by the social interest group to obtain cache resources, which is an increasing function of the unit cache resource price p, then the revenue function $R(p)$ of the macro base station can be expressed as:

$$R(p) = \eta \sum_{n=1}^{N} ps_n \quad (11)$$

The cost of a macro base station is the cost of maintaining the cache capacity of the small base station and the cost of motivating social interest group. The cost function $C(s)$ of the macro base station can be expressed as:

$$C(s) = \begin{cases} \frac{1}{Q_s - \beta \sum_{i=1}^{n} s_{si}} + \sum_{i=1}^{n} dg_i p_1, & Q_s \geq \sum_{i=1}^{n} s_{si} \\ \infty, & Q_s < \sum_{i=1}^{n} s_{si} \end{cases} \quad (12)$$

Where Q_s represents the buffer capacity of all small base stations within the coverage of the macro base station, and β represents the unit cost of maintaining the buffer capacity of the small base station.

Based on the revenue and cost functions of the macro base station, the utility function U_0 of the macro base station can be obtained as:

$$U_0 = \eta \sum\nolimits_{n=1}^{N} ps_n - \frac{1}{Q_s - \beta \sum_{i=1}^{n} s_i} - \sum\nolimits_{i=1}^{n} dg_i p_1 \tag{13}$$

The macro base station needs to formulate an appropriate unit buffer resource price p^* to ensure its higher revenue. By maximizing the utility function U_0, the optimal unit cache resource price p^* can be obtained as:

$$p^* = \arg\ \max U_0(p, s^*) \tag{14}$$

Where s^* represents the optimal demand strategy for cache resources in the interest community.

3.3 Problem Solving and Resource Allocation Algorithm

This section will solve the Stackelberg game problem and give an edge cache resource allocation algorithm based on the incentive mechanism. Using the distributed iterative method, the strategy is continuously adjusted through multiple iterations to obtain the Nash equilibrium solution of the Stackelberg game.

Suppose that at time t, the macro base station announces the unit cache resource price $p(t)$ to all social interest groups. After obtaining the price strategy of the macro base station, the social interest group will adjust its cache resource demand at the macro base station according to its own needs and utility. Make it satisfy the Nash equilibrium solution. The change rate of the cache resource demand of the social interest group is proportional to the first-order partial derivative of its utility function. The social interest group needs to go through iterations in the non-cooperative game process, and change its cache resource demand strategy many times to achieve Nash equilibrium. In the iteration cycle $\Delta\tau$, the cache resource demand strategy iteration equation of social interest group n can be expressed as:

$$U_n(\tau + 1) = U_n(\tau) + \mu \dot{s}_n \tag{15}$$

Where $\mu > 0$ represents the iterative step size of the social interest group cache resource demand strategy, and $\dot{s}_n$ represents the first-order partial derivative of the utility function, as follows:

$$\dot{s}_n = \frac{\partial U_n(p, s_n, s_{-n})}{\partial s_n} \tag{16}$$

Since the utility function of the social interest group is a concave function, after multiple iterations, it can be ensured that the social interest group can converge to the Nash equilibrium point of the game.

After reaching the Nash equilibrium between the social interest groups, the macro base station adjusts its own unit cache resource price strategy to maximize its utility according to the cache resource demand strategy of the social interest group. The price iteration formula is as follows:

$$p(t+1) = p(t) + \theta \frac{\partial U_0(p(t), s(t))}{\partial p(t)} \tag{17}$$

Where θ represents the iteration step size of the unit cache resource price strategy of the macro base station.

The first-order partial derivative of the utility function of the macro base station can be calculated by a small change parameter ε, the formula is as follows:

$$\frac{\partial U_0(p(t), s(t))}{\partial p(t)} \approx \frac{U_0(\cdots, p(t)+\varepsilon, \cdots) - U_0(\cdots, p(t)-\varepsilon, \cdots)}{2\varepsilon} \tag{18}$$

Before the cache resource demand strategy of the social interest group reaches the Nash equilibrium, the unit cache resource price of the macro base station must remain unchanged until all the social interest groups reach the optimal cache resource demand strategy. The time used during this period is the macro base station's iteration cycle Δt, therefore, the iteration cycle Δt of the macro base station includes multiple iteration cycles $\Delta \tau$ of the social interest group. After many iterations, the macro base station and the social interest group will obtain the optimal price strategy p^* and the optimal cache resource demand strategy s_n^* respectively, that is, they both satisfy the Nash equilibrium (p^*, s_n^*). Under this equilibrium, any party of the game participants can not achieve higher revenue if it changes its strategy alone.

Intuitively, The entire iteration process is as follows:

1. Unit cache resource price strategy adjustment of macro base station: The macro base station adjusts its unit cache resource price strategy according to Eq. (17) and Eq. (18) at every moment t, and announces this strategy to the social interest group.
2. Cache resource demand strategy adjustment of social interest group: After receiving the new price strategy, the social interest group adjusts its own cache resource demand strategy according to Eq. (15) and Eq. (16) until the revenue of the social interest group reaches the maximum value. In this situation, all social interest groups have reached the Nash equilibrium.
3. If the revenue of the macro base station reaches the maximum value at this time, the iteration will end. Otherwise, at the next moment $t+1$, the macro base station returns to process 1 to continue to adjust the unit cache resource price strategy according to the cache resource demand strategy of the social interest group.

Based on the unit cache resource price of the macro base station, the cache resource demand of the social interest group, and the contribution of the social interest group, we can obtain the revenue function of the macro base station and the social interest group. By analyzing the Stackelberg game process between the macro base station and the social interest group and using distributed iterative algorithm, we can obtain the optimal price of the macro base station and the optimal cache resource strategy of the social interest group.

4 Experiment

4.1 Parameters

In this section, we will analyze the performance of the proposed SBSUC under the MATLAB platform. The macro base station manages the cache capacity of all social interest groups and small base stations. We assume that the cache capacity managed by the macro base station is $Q = 2$, and the coverage radius r_s of the small base station is 0.5 km. The D2D communication radius r_u between users is 0.1 km. The average activity of the three social interest groups are $\overline{V}_1$=0.4, $\overline{V}_2$=0.6, $\overline{V}_3$=0.8 respectively. We assume that the total number of popular content of each social interest group is the same as $m = 100$. The average transmission delay from the content server to the end user is 98 ms, and the average transmission delay from micro base stations to users is 10ms, and the average transmission delay from users to users is 3 ms. The initial caching resource strategy for each social interest group is 0.05, and the initial unit cache resource price strategy of macro base station is 0.1. The iteration step size μ of the social interest group cache resource demand strategy and the macro base station price strategy are both set to 0.1, and the convergence accuracy is $\varepsilon_1 = 10^{-3}$. We compare SBSUC with IUC [12], which is a resource allocation algorithm for incentivizing users to participate in content caching, and IBSC [13], which is a resource allocation algorithm for incentivizing base stations to participate in content caching.

4.2 Main Results

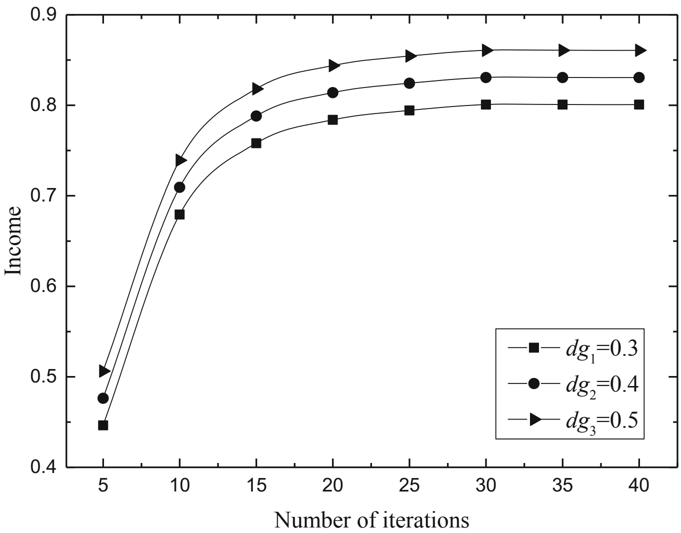

Fig. 2. The revenue in different contributions

Figure 2 shows when the content popularity parameter value of the three social interest groups is $r = 0.6$ and the macro base station is at the best unit cache resource price, as the number of iterations increases, the revenue changes in different contributions dg_n. It can be seen from the figure that as the number of iterations increases, the revenue of the social interest group gradually increases, and finally when the Nash equilibrium between the social interest groups is reached, the revenue tends to be stable. Among them, the revenue of the social interest group $dg_3 = 0.5$ is greater than the social interest group $dg_2 = 0.4$ and greater than the social interest group $dg_1 = 0.3$. This is because the greater the degree of contribution, the more incentives the macro base station gives, and therefore the higher the revenue of the social interest group.

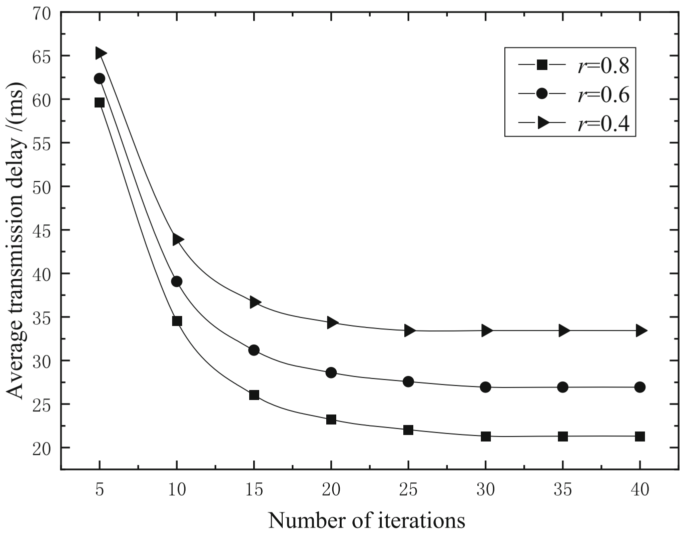

Fig. 3. The transmission delay in a different activity

Figure 3 shows that the contribution of the three social interest groups is the same $dg_n = 0.3$. At the same time, when the macro base station caches the price in the best unit, the average transmission delay of the users in the respective groups in the iterative process of the social interest group is changed. It can be seen from the figure that for social interest groups with different popularity parameter values, as the number of iterations increases, the average transmission delay for users in the group to obtain content gradually decreases and tends to stabilize. Among them, the popularity parameter the value of $r = 0.8$ delay in the social interest groups is less than the $r = 0.6$ delay in the social interest groups is less than $r = 0.4$ the delay in the social interest groups, because the popularity of parameter values r greater, popular content distribution is concentrated, the higher the contents of the cache hit rate, and therefore The lower the average time delay for users to access the content.

Figure 4 shows the change curve of the utility of the three social interest groups in the iterative process. It can be seen from the figure that as the number of iterations increases, the utility functions of the three social interest groups gradually increase and become stable. Among them, the utility of social interest group 3 is greater than that of social interest group 2 than that of social interest group 1, because of the content

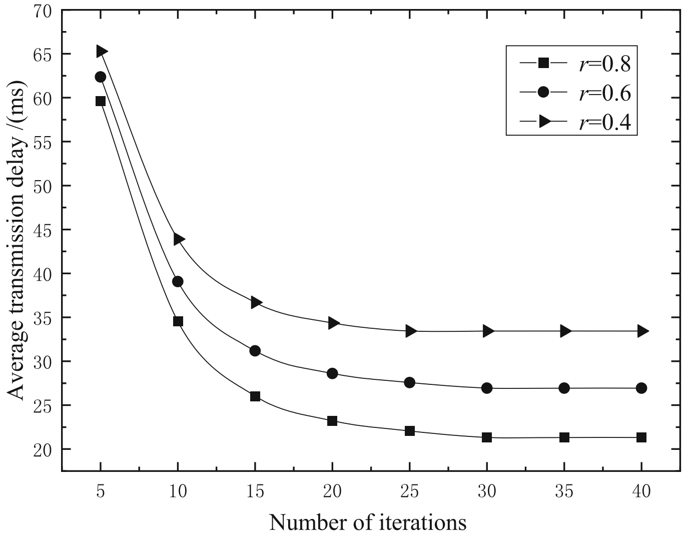

Fig. 4. The utility change curve of the social interest group

popularity parameter $r3 > r2 > r1$. The greater the popularity parameter value, the more concentrated the content distribution accessed by users in the group, the greater the buffer hit rate, the lower the average transmission delay, and the greater the utility. At the same time, the contribution degree $dg_3 > dg_2 > dg_1$, the greater the contribution degree of the social interest group, the more incentive the macro base station gives, so the greater the utility. Ultimately makes utility $SI3 > SI2 > SI1$.

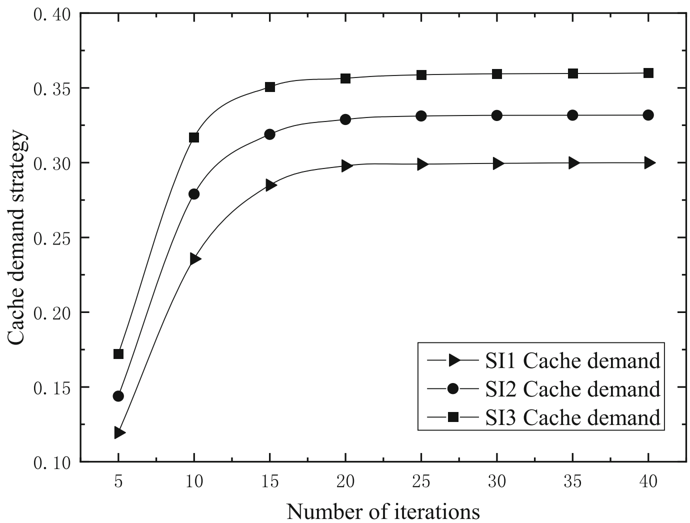

Fig. 5. Non-cooperative game between SIs with different cache resource requirements

Figure 5 shows the macro base station cache resource unit published price, with the increase in the number of iterations, 3 cooperatives pay non-cooperative game competition process between interest groups. As can be seen from the figure that increases as the number of iterations, 3 cache resources demand a social interest groups gradually increased, when the number of iterations reaches 20 or so times, 3 cache resources demand a stable social interest groups, that is, the non-cooperative game between social interest groups reaches Nash equilibrium. Where the social interest groups 3 cache resource demand is the greatest, because of its content popularity parameters biggest, popular content distribution is relatively more concentrated, higher cache hit rate, and therefore hire more cache resources can get more revenue.

Figure 6 shows the comparison of the IBSUC algorithm proposed in this chapter with the other two algorithms in terms of average transmission delay performance as the number of iterations increases. It can be seen from the figure that as the number of iterations increases, the average transmission delay of the three algorithms gradually decreases, and finally stabilizes. The performance of the proposed algorithm is better than that of the other two algorithms. This is because the proposed algorithm considers that the base station and the user are encouraged to participate in content caching at the same time. The user can obtain the requested content from neighboring users or the base station, which can reduce the number of users to the base station. And the average transmission delay from the base station to the content server to obtain the content. Compared with the IUC algorithm that only encourages users to participate in content caching and the IBSC algorithm that only encourages base stations to participate in content caching, the proposed algorithm can obtain more buffer capacity and therefore has a lower average transmission delay.

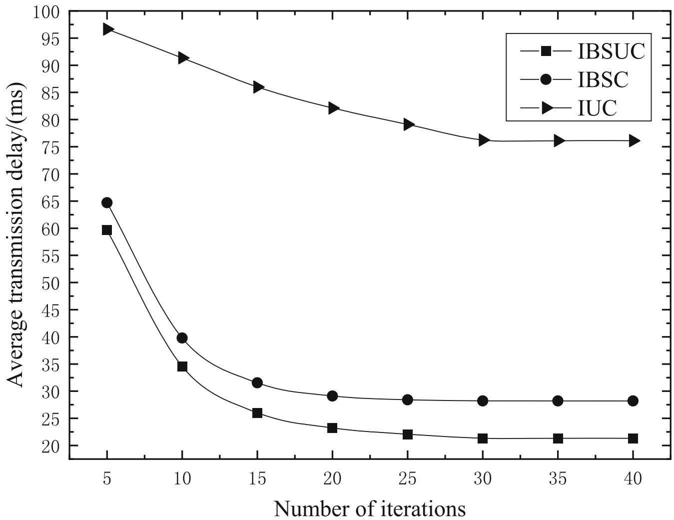

Fig. 6. Comparison of the average transmission delay of different algorithms

5 Conclusion

This paper proposes an incentive-based resource allocation strategy for edge caches in mobile social networks. Considering an edge cache resource allocation scenario within the coverage of a macro base station, the social interest groups purchase cache resources from the macro base station to cache popular content in the group. The incentive cache model is modeled as a Stackelberg game, and the utility functions of the macro base station and the social interest group are constructed respectively. The distributed iterative method is used to obtain the optimal unit cache resource price strategy of the macro base station and the optimal cache resource demand strategy of the social interest groups. The experimental results show that the proposed mechanism has lower average content transmission delay and higher user experience quality.

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