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A Q-Learning Based Scheme to Securely Cache Content in Edge-Enabled Heterogeneous Networks

MINGHUI DAI, ZHOU SU, QICHAO XU, AND WEIWEI CHEN
School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200444, China

Corresponding author: Zhou Su (zhousu@ieee.org)

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ABSTRACT With the increasing demands for mobile users to obtain content, the heterogeneous networks (HetNets), which consolidate the backbone networks with mobile edge networks, have been regarded as a promising paradigm to provide mobile users with high quality of experience (QoE). However, the limited network resources and caching capacity become a new challenge to deliver content in HetNets. Therefore, in this paper, a cooperative scheme between edge server and content provider in HetNets is proposed to improve the performance of content delivery. Firstly, a novel framework of content delivery with backbone networks and mobile edge networks is introduced. The edge servers are deployed at the edge of networks and close to users. Secondly, a Q-learning based scheme for content caching is developed to securely cache contents with the cooperation between edge server and content provider. Thirdly, the cooperative interaction between edge server and content provider is modeled as the double auction game. Each player can obtain the maximum utility from the equilibrium strategy. Finally, simulation results show that the proposed scheme can improve the efficiency of content delivery and bring more utilities to edge server and content provider than the conventional schemes.

INDEX TERMS Heterogeneous networks (HetNets), Q-learning, content delivery, cooperative scheme, double auction.

I. INTRODUCTION

With the rapid development of wireless communication technologies and network infrastructure in heterogeneous networks (HetNets), the proliferating smart devices (e.g., smart phones, smart watches, tablet computer) prompt the exponential growth of mobile video streaming [1]–[6]. Moreover, as the demand of high quality of service (QoS) exceeds the available capacity in conventional network, the conventional network structure suffers the unprecedented challenges [7]. On one hand, the cloud server is located at the remote cloud, delivering contents to endpoint users consumes a number of network resources (e.g., bandwidth, energy, etc.) and causes the network congestion [8]. On the other hand, a large number of content requests lead the redundant delivery to cloud server. As a result, the efficiency of content delivery is low [9], [10].

HetNets enabled mobile edge networks have prevailed as a dominant method for providing high-quality mobile services [11], [12]. However, the attractive applications and services mainly depend on high-speed data rates and low-latency transmission. This poses critical challenges to the conventional network with the following reasons: firstly, the network resources in mobile edge networks are different from the conventional network. For example, the storage capacity is lower than that in the conventional network, and the wireless backhaul is shorter than that in the conventional network. Secondly, since the popularity of contents changes dynamically, the number of contents provided by content provider grows rapidly. It is hard to cache all contents in edge servers. Thirdly, due to the variability of contents, the hit ratio of cached contents is rather low in the conventional network. Therefore, caching contents in edge servers is a promising

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way to cope with the huge traffic load over the conventional network [13], [14].

However, edge caching-enabled content delivery is challenging with the following two aspects: 1) Content caching strategy: the social interests of mobile users influence the content distribution in edge servers. Moreover, the social characteristics (e.g., preference, recommendation, etc.) of endpoint users also affect the caching deployment of edge servers. Thus, the content caching strategy should be efficiently analyzed to improve the performance of content delivery [15], [16]. 2) Content updating strategy: since the storage resources at edge servers are limited, the effect of content caching is constrained by the number of content files [18]. The optimal content caching strategy can improve the hit ratio and mobile users' quality of experience (QoE). Recently, researches on the Q-learning approach focus on caching content over the conventional network [19]–[21]. However, most of the existing caching schemes cannot be fully used in HetNets. Therefore, the Q-learning based content caching scheme for edge servers should be further analyzed.

There are many proposals for content delivery in HetNets. The existing works mainly focus on the optimization of content delivery scheme [22], [23], content caching scheme [24], [25], and cooperative delivery scheme [26], [27], etc. A collaborative multicast beamforming in cache-enabled ultra-dense networks is presented in [28]. A cooperative content caching and delivery scheme is proposed in [29] to reduce the transmission cost from the macro base stations to mobile devices. However, the cooperative scheme for edge server and content provider in HetNets is not further considered. On the other hand, most conventional incentive schemes assume that the idle caching resources are freely contributed by the edge servers. It is infeasible to cache contents in edge servers without incentives due to the selfishness. Therefore, how to design an effective incentive scheme to improve the efficiency of content delivery becomes a new challenge [30].

In order to address the above issues, a cooperative scheme between edge server and content provider is proposed to improve the efficiency of content delivery in HetNets. The framework of HetNets for content delivery is firstly introduced. Next, a Q-learning based scheme for content caching is proposed to improve the hit ratio. Afterwards, the cooperative scheme between edge server and content provider is established to deliver content to mobile users. Finally, the interaction process between edge server and content provider is modeled as a double auction game based incentive. Each player can achieve the maximum utility based on the optimal strategy.

In a nutshell, the main contributions of this paper are as follows:

- **Framework:** We introduce the hybrid networks, which are composed of backbone networks and mobile edge networks. Based on the hybrid networks, contents are cached in mobile edge networks from the backbone networks. Next, considering the limited caching capacity of edge server, a Q-learning based scheme for content caching is developed to cache the optimal contents in edge servers to improve the hit ratio.
- **Scheme:** We present a cooperative scheme for edge server and content provider. The contents are delivered to mobile users based on the cooperative scheme to improve mobile users' QoE. Next, we model the cooperative scheme as a double auction game based incentive to improve the efficiency of content delivery.
- **Validation:** We evaluate the performance of the proposed scheme and game model using extensive simulations. Simulation results demonstrate that the proposed scheme can not only maximize the hit ratio of content but also improve the utility compared with the conventional methods.

The remainder of this paper is organized as follows. Section II reviews the related work. Section III presents the system model. Section IV introduces the Q-learning based content caching scheme. The cooperative scheme for content delivery is described in Section V. Performance evaluations are shown in Section VI, and Section VII closes this paper with conclusion and future work.

II. RELATED WORK

In this section, we review the related work including the content delivery scheme, cooperative scheme and incentive scheme in HetNets.

A. CONTENT DELIVERY SCHEME IN HetNets

There have been considerable works on content delivery in HetNets. The caching placement strategy in two-tier wireless content delivery networks was proposed by Sung *et al.* [31] to improve the performance of content delivery. In [32], the optimization problem of caching replication was formulated based on the routing strategy to maximize the content delivery rate. Ma and Jamalipour [33] presented a cooperative caching-based content delivery framework to implement the cooperative caching for encountering nodes. A study of energy-efficient video-on-demand (VoD) content caching and distribution was evaluated by Ayoub *et al.* [34] to reduce the energy consumption of the network. To cope with the explosive growth of mobile traffic, a novel content distribution architecture was presented by Xie *et al.* [35] to cache content and ensure the reliability of the content distribution architecture, respectively. Although most of these works have discussed the content delivery in content delivery networks, few of them focus on the content caching scheme for edge servers in HetNets.

B. COOPERATIVE SCHEME DESIGN IN HetNets

The cooperative scheme design has recently become a hot research topic for content delivery. Chae *et al.* [36] proposed a probabilistic content placement to maximize the average success probability of content delivery. A cooperative server selection scheme was developed by Nishiyama *et al.* [37] to maximize the robustness with the cooperation between the content delivery system and its users. Jia *et al.* [38] proposed a novel cooperative content fetching scheme to improve the quality of video delivery in wireless networks. Jiang *et al.* [39] proposed a novel content distribution system to improve mobile users' QoE. The edge caching content service market model was proposed by Xiong *et al.* [40] to reduce the cost and improve the quality of content service. However, the cooperative scheme for edge server and content provider is still not discussed sufficiently in most of the existing works.

C. INCENTIVE SCHEME DESIGN IN HetNets

There have been a number of studies that investigate the incentive scheme in HetNets. Barua *et al.* [41] took the selfish deviating users into account and proposed a carrier aggregation-based incentive mechanism. Shih *et al.* [42] modeled the content delivery transaction as the auction game to efficiently allocate the scarce radio resources and derive the optimal pricing strategy. Xu *et al.* [43] proposed a coalitional game based on the payoffs of content requesters to deliver the popular contents. A new Bayesian coalition game for content distribution was presented by Kumar *et al.* [44]. Zhang and Li [45] presented a decentralized resale market model. The transactions between arbitrary pairs of agents were modeled as the decentralized strategic bargaining game to derive the equilibrium prices. However, the incentive scheme for improving the efficiency of cooperation between content provider and edge server is neglected.

III. SYSTEM MODEL

In this section, we introduce the system model including the user model, content model and incentive model. Table 1 summarizes the symbols used.

A. USER MODEL

As illustrated in Fig. 1, HetNets operate over the hybrid networks including backbone networks and mobile edge networks. The backbone networks locate in the content provider layer. The mobile edge networks are close to mobile user layer. The contents are delivered over the Internet from cloud server to edge servers.

1) MOBILE USERS

The set of mobile users is denoted as $i = \{1, 2, \ldots, I\}$. Mobile users are interested in obtaining contents (e.g., popular movies, music, sports news, etc.) based on their interests. Each mobile user can access the backbone networks and edge networks to obtain contents. Considering the privacy requirement of mobile user, the privacy preference of mobile user i is denoted by ς_i $(0 \leq \varsigma_i \leq 1)$ [46], [47]. The higher ς_i indicates the greater requirement for mobile user i to obtain content.

2) EDGE SERVERS

The set of edge servers is denoted by $j = \{1, 2, \ldots, J\}$. Edge servers are placed at the edge of networks (e.g., coffee shops,

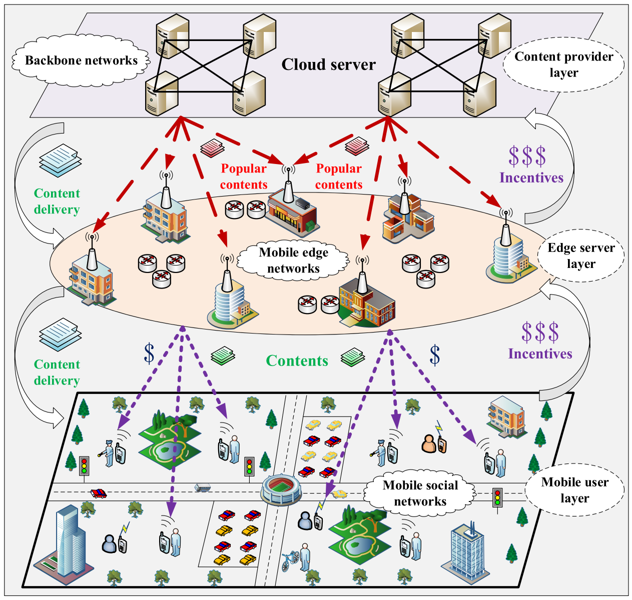


FIGURE 1. Content delivery scheme in HetNets.

supermarkets, campuses, etc.) by the content provider. Each edge server has limited storage to cache contents and the caching size of edge server j is defined as s_j, which follows the interval $\left[{s_j}^{\min}, {s_j}^{\max}\right]$. Due to the short communication distance between mobile user and edge server, the transmission delay can be significantly reduced to improve mobile users' QoE.

3) CONTENT PROVIDER

Content provider locates at the end of cloud, which stores a large number of contents in cloud servers. The contents are cached in edge servers by the content provider in advance. On the other hand, if the content requested by mobile user is not cached in edge server, the content is delivered to mobile user based on the cooperative scheme between content provider and edge server [17].

B. CONTENT MODEL

There are a large number of contents in the networks. Let $q = \{1, 2, \ldots, Q\}$ denote the set of contents in the networks. The size of content q is defined as s_q, which follows the uniform distribution in $\left[{s_q}^{\min}, {s_q}^{\max}\right]$ [48]. Based on the caching size of edge server j and the size of content q, the number of contents cached in edge server j can be calculated by

$$Z_j = \left\lfloor \frac{2s_j}{{s_q}^{\max} + {s_q}^{\min}} \right\rfloor^{+}, \tag{1}$$

where $\lfloor \times \rfloor^{+}$ denotes the floor function. Moreover, due to the limited caching size of edge server j, the contents cached in edge server j should satisfy $\sum_{k=1}^{Z_j} x_{k,q} s_q \leq s_j$, where $x_{j,q}$ is a binary value. $x_{k,q} = 1$ denotes that content q is cached in edge server j and $x_{k,q} = 0$ otherwise.

Each content q has the property level, which is described as $\mathcal{H}_q = \left(f_q, r_q, l_q, t_q\right)$ [49]. f_q is the filename, r_q is the identifier,

TABLE 1. Summary of notations.

Symbols	Descriptions
I	Number of mobile users in HetNets.
J	Number of edge servers in HetNets.
Q	Number of contents in HetNets.
s_j	Caching size of edge server j.
s_q	Size of content q.
${s_j}^{\min}, {s_j}^{\max}$	Maximum/minimum caching size of edge server j.
${s_q}^{\min}, {s_q}^{\max}$	Maximum/minimum size of content q.
Z_j	Number of contents cached in edge server j.
$\mathcal{H}_q$	Property level of content q.
$\mathcal{S}$	Set of caching states of edge servers.
$\mathcal{A}$	Set of caching actions of edge servers.
$\mathcal{R}$	Set of reward functions of edge servers.
λ	Learning rate of Q-learning.
υ	Discount factor of Q-learning.
$\mathcal{G}_j(\mathbf{s}_j, \mathbf{a}_j)$	Gain for newly caching content in edge server j.
$\mathcal{L}_j(\mathbf{s}_j, \mathbf{a}_j)$	Loss for replacing content in edge server j.
D_j	Size of contents that mobile user requests from edge server j.
c_j	Cooperative decision of edge server j.
${q_{CP}}^*$	Cooperative content requested by edge server.
$N_{i,q}$	Number of mobile users requesting content q.
$M_{i,q}$	Number of contents that mobile user requests.
μ_{CP}, μ_j	Transmission rate of content provider and edge server j, respectively.
$\overline{P_{j,{q_{CP}}^*}}$	Price that edge server j pays to content provider for delivering content ${q_{CP}}^*$.
$C_{{q_{CP}}^*}$	Cost of content provider for delivering content ${q_{CP}}^*$.
$P_{j,q}$	Price of content q that mobile user pays to edge server j.
$C_{j,q}$	Cost of edge server j for delivering content q.
$P_{j,{q_{CP}}^*}$	Price that mobile user pays to edge server j for obtaining content ${q_{CP}}^*$.
p_{unit}, ζ_{unit}	Unit price of content, and unit transmission cost, respectively.
$S(q, {q_{CP}}^*)$	Satisfaction function for mobile user to obtain content q and ${q_{CP}}^*$.
$U_i(q, {q_{CP}}^*)$	Utility function of mobile user i.
$U_j(q, {q_{CP}}^*)$	Utility of edge server j for delivering content q and ${q_{CP}}^*$.
$U_{CP}({q_{CP}}^*)$	Utility of content provider for delivering content ${q_{CP}}^*$.
$\theta_{CP,{q_{CP}}^*}, \theta_{j,{q_{CP}}^*}$	Valuation of content ${q_{CP}}^*$ for content provider and edge server j, respectively.
$B_{CP}(\theta_{CP,{q_{CP}}^*}), B_j(\theta_{j,{q_{CP}}^*})$	Bidding strategy of content provider and edge server j, respectively.

l_q is the packet, and t_q denotes the time stamp. When mobile users request contents, they generate a context information with the property $\mathcal{H}_q$ and send to edge servers. The objective contents are delivered to mobile users when the accuracy of context recognition is verified.

C. INCENTIVE MODEL

Due to the selfishness, edge server and content provider are unwilling to deliver content without incentives. The effective incentive scheme is designed to improve the efficiency of content delivery in HetNets. When mobile user i requests content q and the content is cached in edge server j, the content is delivered to mobile user i. Next, mobile user i pays payment to edge server j based on the pricing strategy $P_{j,q}$, which is defined in Section V-A.

When the content q is not cached in edge server j, the cooperative scheme for edge server and content provider is established. Next, edge server j and content provider reach an agreement on the payment for delivering content q. The content q is delivered to mobile user i by the content provider. Then, the payment based on the pricing strategy P_{j,q_{CP}^*}, defined in Section V-A, is paid to edge server j by mobile user i. The payment $\overline{P_{j,q_{CP}^*}}$, which is determined in Section V-B, is paid to content provider by edge server j.

IV. Q-LEARNING BASED CONTENT CACHING SCHEME

This section first introduces the Q-learning based content caching scheme. Next, the cooperative strategy for edge server and content provider is established.

A. CONTENT CACHING PROBLEM

Since the limited caching storage in edge server, the content caching strategy should be effectively designed to improve the hit ratio of content. We consider the content caching problem as a triplet $\{\mathcal{S}, \mathcal{A}, \mathcal{R}(s, a)\}$, where $\mathcal{S}$ indicates the caching state of edge server, $\mathcal{A}$ denotes the action of edge server, and $\mathcal{R}(s, a)$ is the reward function when performing action.

1) $\mathcal{S} = \{s_1, s_2, \ldots, s_J\}$ is the set of caching states of edge servers, where $s_j = (s_j(1), s_j(2), \ldots, s_j(Q))$ denotes the set of caching decision of edge server j. $s_j(q) = 1$ means that content q is cached in edge server j and $s_j(q) = 0$ otherwise.

2) $\mathcal{A} = \{a_1, a_2, \ldots, a_J\}$ is the set of caching actions of edge servers, where $a_j = \{a_j({q_m}^+, {q_n}^-) | q_m, q_n \in Q, q_m \neq q_n\}$ represents the action decision of edge server j, i.e., what to newly cache content and what to discard content. $a_j({q_m}^+, {q_n}^-) = 1$ means that content ${q_m}^+$ is newly cached in edge server j and content ${q_n}^-$ is removed from edge server j. Otherwise, $a_j({q_m}^+, {q_n}^-) = 0$. Moreover,

the replaced content in an edge server cannot be the same as the newly cached content.

3) $\mathcal{R}(s,a) = \{\mathcal{R}_1(s,a), \mathcal{R}_2(s,a), \ldots, \mathcal{R}_J(s,a)\}$ is the set of reward functions of edge servers, which determines the reward feedback of edge server when performing action a at state s.

B. Q-LEARNING BASED CONTENT CACHING SCHEME

The optimal content caching strategy is determined based on Q-learning. The Q-value of edge server j is described as the state-action pair (i.e., $Q_j(s_j, a_j)$). The optimal Q-value $Q_j(s_j, a_j)^*$ of edge server j is obtained by the iterative method, which is described as

$$Q_j^{t+1}(s_j, a_j) = (1-\lambda) \cdot Q_j^t(s_j, a_j) + \lambda \cdot \left[\mathcal{R}_j^t(s_j, a_j) + \upsilon \cdot \mathcal{V}_j^t(s_j', a_j)\right], \quad (2)$$

where s_j is the current state of edge server j and s_j' is the next caching state after taking action a_j at sate s_j. λ is the learning rate. υ is the discount factor that affects the effectiveness of future reward to the current reward. $\mathcal{V}_j^t(s_j', a_j) = \max_{a_j} Q_j^t(s_j', a_j)$.

The objective of Q-learning is to find the maximum reward by newly caching and replacing contents. To maximize the hit ratio of content, we formulate the reward function as the difference between the gain and the loss for content caching strategy, i.e.,

$$\mathcal{R}_j(s_j, a_j) = \mathcal{G}_j(s_j, a_j) - \mathcal{L}_j(s_j, a_j), \quad (3)$$

where $\mathcal{G}_j(s_j, a_j)$ and $\mathcal{L}_j(s_j, a_j)$ represent the gain and the loss, respectively. The gain can be obtained by increasing the number of hits for newly caching content, which is denoted by

$$\mathcal{G}_j(s_j, a_j) = \sum_{q^+ \in \mathcal{Q}^+(s_j,a_j)} \Upsilon_{CP}(q^+) + \sum_{q^+ \in \mathcal{Q}^+(s_j,a_j)} \Upsilon_j(q^+), \quad (4)$$

where $\mathcal{Q}^+(s_j, a_j)$ indicates the set of newly cached contents by taking action a_j at state s_j. $\Upsilon_{CP}(q^+)$ and $\Upsilon_j(q^+)$ denote the number of requests that content q^+ is hit at content provider and edge server j, respectively. From Eq. (4), we can see that if a content q^+ is hit many times by mobile users, a higher gain is brought to edge server j.

Similarly, the loss is calculated based on the decreasing number of hits for replacing content, which is described as

$$\mathcal{L}_j(s_j, a_j) = \sum_{q^- \in \mathcal{Q}^-(s_j,a_j)} \Upsilon_{CP}(q^-) + \sum_{q^- \in \mathcal{Q}^-(s_j,a_j)} \Upsilon_j(q^-), \quad (5)$$

where $\mathcal{Q}^-(s_j, a_j)$ is the set of replaced contents by taking action a_j at state s_j. Eq. (5) indicates that if a content q^- is hit many times by mobile users, a large loss will be led to edge server j.

C. COOPERATIVE STRATEGY FOR CONTENT DELIVERY

When a large number of mobile users request contents and the contents are not cached, edge servers cannot satisfy the requirements of mobile users. The cooperative scheme between content provider and edge server is established to deliver contents. The size of content that mobile users request from edge server j can be denoted as

$$D_j = \sum_{i=1}^{I} \sum_{q=1}^{Q} \alpha_{i,q} s_q, \quad (6)$$

where $\alpha_{i,q}$ is a binary value. $\alpha_{i,q} = 1$ means that mobile user i requests content q from edge server j and $\alpha_{i,q} = 0$ otherwise. Let c_j $(c_j \in \{0, 1\})$ denote the cooperative decision of edge server j, we have

$$c_j = \begin{cases} 1, & \text{if } D_j > s_j, \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

If the contents' size requested by mobile users is higher than the caching size of edge server j, edge server j chooses to cooperate with the content provider (i.e., $c_j = 1$) and $c_j = 0$ otherwise.

To meet the requirements of mobile users, the contents requested by edge servers are associated with the number of mobile users and contents. We formulate the requirements of mobile users as the satisfaction function to obtain the optimal decision. The cooperative content requested by edge server j can be calculated by

$$q_{CP}^* = \left\lceil \arg\max_q \log_2\left(1 + \rho_j \frac{N_{i,q}}{N_i} + (1-\rho_j)\frac{M_{i,q}}{M_i}\right)\right\rceil^+, \quad (8)$$

where $\lceil \times \rceil^+$ is the ceiling function. ρ_j $(0 < \rho_j < 1)$ denotes the weighting parameter of edge server j. $N_{i,q}$ is the number of mobile users requesting content q, which satisfies $N_{i,q} \leq N_i \leq N_{i,\max}$. $M_{i,q}$ is the number of contents that mobile user requests, which satisfies $M_{i,q} \leq M_i \leq M_{i,\max}$.

V. COOPERATIVE SCHEME FOR CONTENT DELIVERY

In this section, the problem formulation is firstly introduced. Next, we model the cooperative interaction as the double auction game based incentive. Finally, we obtain the equilibrium strategy of the game.

A. PROBLEM FORMULATION

1) FOR CONTENT PROVIDER

If edge server cooperates with content provider and reaches the payment agreement, the utility of content provider is related to the price paid by edge server. Otherwise, the utility of content provider is zero. We have the following two cases:

Case 1: Edge server does not cooperate with the content provider, or the payment agreement between each other is not reached (i.e., $c_j = 0$). The utility of content provider is zero.

Case 2: Edge server cooperates with the content provider and reaches the payment agreement between each other (i.e., $c_j = 1$). The utility of content provider can be calculated by the difference between the price paid by edge server and the cost of delivering content.

Based on case 1 and case 2, the utility function of content provider can be denoted by

$$U_{CP}\left(q_{CP}{}^{*}\right) = \begin{cases} \sum_{i=1}^{N_{i,q_{CP}{}^{*}}} \beta_{i,q_{CP}{}^{*}} \left(\overline{P_{j,q_{CP}{}^{*}}} - C_{q_{CP}{}^{*}}\right), & c_j = 1, \\ 0, & c_j = 0. \end{cases} \tag{9}$$

$\beta_{i,q_{CP}{}^{*}}$ is a binary value of mobile user i. $\beta_{i,q_{CP}{}^{*}} = 1$ means that mobile user i obtains content $q_{CP}{}^{*}$ from content provider and $\beta_{i,q_{CP}{}^{*}} = 0$ otherwise. $\overline{P_{j,q_{CP}{}^{*}}}$ is the price that edge server j pays to content provider for delivering content $q_{CP}{}^{*}$. $C_{q_{CP}{}^{*}}$ denotes the cost of delivering contents $q_{CP}{}^{*}$, which is related to the transmission time (i.e., $C1_{q_{CP}{}^{*}}$) and the number of mobile users (i.e., $C2_{q_{CP}{}^{*}}$). We have $C_{q_{CP}{}^{*}} = C1_{q_{CP}{}^{*}} + C2_{q_{CP}{}^{*}}$.

Let μ_{CP} denote the transmission rate of content provider, the cost of content delivery can be calculated by

$$C1_{q_{CP}{}^{*}} = \omega_1 \cdot \frac{s_{q_{CP}{}^{*}}}{\mu_{CP}}, \tag{10}$$

$$C2_{q_{CP}{}^{*}} = \omega_2 \cdot \log_2 \left(1 + \frac{N_{i,q_{CP}{}^{*}}}{N_i}\right), \tag{11}$$

where ω_1 and ω_2 are the adjustment parameters. $s_{q_{CP}{}^{*}}$ is the size of content $q_{CP}{}^{*}$ and $N_{i,q_{CP}{}^{*}}$ is the number of mobile users requesting content $q_{CP}{}^{*}$. Thus, combining $C1_{q_{CP}{}^{*}}$ and $C2_{q_{CP}{}^{*}}$, the cost for content provider to deliver content $q_{CP}{}^{*}$ is

$$C_{q_{CP}{}^{*}} = \omega_1 \cdot \frac{s_{q_{CP}{}^{*}}}{\mu_{CP}} + \omega_2 \cdot \log_2 \left(1 + \frac{N_{i,q_{CP}{}^{*}}}{N_i}\right). \tag{12}$$

2) FOR EDGE SERVERS

The utility of edge server is associated with the strategy of whether cooperating with content provider. We have the following two cases:

Case 1: When edge server cooperates with content provider and reaches the payment agreement (i.e., $c_j = 1$), the utility of edge server is the difference among the price paid by mobile users, the cost of delivering content and the price paid to content provider.

Case 2: When edge server does not cooperate with content provider (i.e., $c_j = 0$), the utility of edge server is the difference between the price paid by mobile users and the cost of delivering content.

Combining case 1 and case 2, the utility of edge server j can be calculated by

$$U_j\left(q, q_{CP}{}^{*}\right) = \begin{cases} \sum_{i=1}^{N_{i,q}} \sum_{q=1}^{M_{i,q}} \alpha_{i,q}\left(P_{j,q} - C_{j,q}\right), \\ \quad c_j = 0, \\ \sum_{i=1}^{N_{i,q}} \sum_{q=1}^{M_{i,q}} \alpha_{i,q}\left(P_{j,q} - C_{j,q}\right) \\ + \sum_{i=1}^{N_{i,q_{CP}{}^{*}}} \beta_{i,q_{CP}{}^{*}}\left(P_{j,q_{CP}{}^{*}} - \overline{P_{j,q_{CP}{}^{*}}}\right), \\ \quad c_j = 1, \end{cases} \tag{13}$$

where $P_{j,q}$ is the price of content q that mobile user pays to edge server j. $C_{j,q}$ is the cost for edge server j to deliver content q. $P_{j,q_{CP}{}^{*}}$ denotes the price that mobile user pays to edge server j for obtaining content $q_{CP}{}^{*}$.

Considering the unit price of content, the price that mobile user pays to edge server j for obtaining content q and $q_{CP}{}^{*}$ can be separately defined as

$$P_{j,q} = p_{unit} \cdot s_q, \tag{14}$$

$$P_{j,q_{CP}{}^{*}} = p_{unit} \cdot s_{q_{CP}{}^{*}}, \tag{15}$$

where p_{unit} is the unit price of content. Let ζ_{unit} denote the unit transmission cost, the cost for edge server j to deliver content q is denoted by

$$C_{j,q} = \zeta_{unit} \cdot \frac{s_q}{\mu_j}. \tag{16}$$

3) FOR MOBILE USERS

The utility of mobile user is associated with the satisfaction of obtaining contents from edge server or content provider and the price paid to edge server. The longer the time for mobile user to obtain content, the lower the satisfaction of mobile user. The satisfaction function should be a concave and non-decreasing function for the transmission time, which can be derived by

$$S\left(q, q_{CP}{}^{*}\right) = \varsigma_i \log_2 \left[\sigma - \left(\alpha_{i,q}\frac{s_q}{\mu_j} + \beta_{i,q_{CP}{}^{*}}\frac{s_{q_{CP}{}^{*}}}{\mu_{CP}}\right)\right], \tag{17}$$

where ς_i is the adjustment parameter. σ is a positive number to guarantee the satisfaction function is nonnegative. Let $d_i = 1$ denote that mobile user i obtains content and $d_i = 0$ otherwise. Therefore, the utility function of mobile user i can be obtained by

$$U_i\left(q, q_{CP}{}^{*}\right) = \begin{cases} S(q) - \alpha_{i,q}P_{j,q} - \beta_{i,q_{CP}{}^{*}}P_{j,q_{CP}{}^{*}}, & d_i = 1, \\ 0, & d_i = 0. \end{cases} \tag{18}$$

B. STRATEGY ANALYSIS

We model the cooperative strategy between edge server and content provider as the double auction game based incentive. Let $\theta_{CP,q_{CP}{}^{*}}$ and $\theta_{j,q_{CP}{}^{*}}$ denote the valuation of content

${q_{CP}}^*$ for content provider and edge server j, respectively. The bidding strategy of content provider and edge server can be separately given by $B_{CP}\left(\theta_{CP,q_{CP^*}}\right)$ and $B_j\left(\theta_{j,q_{CP^*}}\right)$. If the content provider and edge server reach the payment agreement, the payment $\overline{P_{j,q_{CP^*}}}$ of content ${q_{CP}}^*$ is paid to content provider by edge server j, which satisfies

$$\overline{P_{j,q_{CP^*}}} = \gamma B_j\left(\theta_{j,q_{CP^*}}\right) + (1-\gamma) B_{CP}\left(\theta_{CP,q_{CP^*}}\right), \quad (19)$$

where γ $(0 < \gamma < 1)$ is the proportion coefficient of bidding strategy. Next, we analyze the valuation of content ${q_{CP}}^*$ for content provider and edge server to obtain the optimal bidding strategy.

1) FOR CONTENT PROVIDER

The valuation of content ${q_{CP}}^*$ is associated with the valuation of transmission rate, transmission time, transmission cost and punishment factor, which are listed as follows:

1) Transmission rate. The higher the transmission rate, the larger the resource consumption (e.g., bandwidth, power, etc.), and the greater the valuation of content. Let $\mu_{CP,\max}$ denote the maximum transmission rate of content provider, we have the valuation of transmission rate as

$$\nu_{1,CP} = \log_2\left(1 + \frac{\mu_{CP,q_{CP^*}}}{\mu_{CP,\max}}\right). \quad (20)$$

2) Transmission time. If the size of content is lower, and the transmission rate is larger, resulting in the lower transmission time and the higher valuation of content. We have

$$\nu_{2,CP} = \log_2\left(1 + \frac{s_{q_{CP^*}} / \mu_{CP,q_{CP^*}}}{s_{q_{CP,\max}} / \mu_{CP,\max}}\right). \quad (21)$$

3) Punishment factor is the adjustment parameter of valuation of content. Based on the cooperative strategy, the transmission rate of content provider should be not lower than that of edge server. If the transmission rate of content provider is lower than that of edge server, the valuation of content is reduced. Otherwise, the valuation of content is increased, i.e.,

$$\nu_{3,CP} = \left(\mu_{CP,q_{CP^*}} - \mu_{j,q_{CP^*}}\right) \log_2\left(1 + \frac{\mu_{CP,q_{CP^*}}}{\mu_{j,q_{CP^*}}}\right). \quad (22)$$

4) Transmission cost, $\nu_{4,CP} = C_{q_{CP^*}}$. It means that the valuation of content ${q_{CP}}^*$ should be higher than the transmission cost to guarantee that the content provider can obtain the positive utility. Otherwise, the transaction between edge server and content provider will be cancelled.

Combining Eqs. (20), (21), and (22) with the transmission cost, the valuation of content ${q_{CP}}^*$ for content provider can be calculated by

$$\theta_{CP,q_{CP^*}} = \sum_{k=1}^{3} \varphi_{k,q_{CP^*}} \nu_{k,CP} + \nu_{4,CP}, \quad (23)$$

where $\varphi_{k,q_{CP^*}}$ $(k = 1, 2, 3)$ are the weighting parameters of content provider in different cases.

2) FOR EDGE SERVER

The valuation of content ${q_{CP}}^*$ is related to the content size, the number of mobile users, punishment factor and payment price, which are separately defined as follows:

1) Content size. The larger the content size, the greater the resource consumption of content delivery, and the higher the valuation of content. We have

$$\nu_{1,j} = \log_2\left(1 + \frac{s_{q_{CP^*}}}{s_{q_{CP,\max}}}\right). \quad (24)$$

2) Number of mobile users. When the number of mobile users requesting content is larger, more resources will be consumed for content delivery, resulting in the higher valuation of content, i.e.,

$$\nu_{2,j} = \log_2\left(1 + \frac{N_{i,q_{CP^*}}}{N_{i,\max}}\right). \quad (25)$$

3) Punishment factor is the adjustment parameter of valuation of content. If the transmission rate of edge server is higher than that of content provider, the valuation of content is increased. Otherwise, the valuation of content is decreased. We have

$$\nu_{3,j} = \left(\mu_{j,q_{CP^*}} - \mu_{CP,q_{CP^*}}\right) \log_2\left(1 + \frac{\mu_{j,q_{CP^*}}}{\mu_{CP,q_{CP^*}}}\right). \quad (26)$$

4) Payment price, $\nu_{4,j} = P_{j,q_{CP^*}}$. It means that the valuation of content ${q_{CP}}^*$ should be less than or equal to the price that mobile user pays to edge server j. Otherwise, the transaction between edge server and content provider will be cancelled.

Combining Eqs. (24), (25), and (26) with the payment price, the valuation of content ${q_{CP}}^*$ for edge server can be computed by

$$\theta_{j,q_{CP^*}} = \nu_{4,j} - \sum_{k=1}^{2} \phi_{k,q_{CP^*}} \nu_{k,CP} + \phi_{3,q_{CP^*}} \nu_{3,j}, \quad (27)$$

where $\phi_{k,q_{CP^*}}$ $(k = 1, 2, 3)$ are the weighting parameters of edge server in different cases.

C. OPTIMAL COOPERATIVE STRATEGY

Based on the valuation of content ${q_{CP}}^*$ for content provider, the utility function of content provider can be rewritten as

$$\begin{aligned} U_{CP}\left({q_{CP}}^*\right) &= \sum_{i=1}^{N_{i,q_{CP^*}}} \beta_{i,q_{CP^*}} \left(\overline{P_{j,q_{CP^*}}} - C_{q_{CP^*}}\right) \\ &= \sum_{i=1}^{N_{i,q_{CP^*}}} \beta_{i,q_{CP^*}} \overline{P_{j,q_{CP^*}}} - \sum_{i=1}^{N_{i,q_{CP^*}}} \beta_{i,q_{CP^*}} C_{q_{CP^*}} \\ &= U_{CP}\left({q_{CP}}^*\right)' + U_{CP}\left({q_{CP}}^*\right)'', \end{aligned} \quad (28)$$

where

$$\begin{cases} U_{CP}(q_{CP}^*)' = \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\overline{P_{j,q_{CP}^*}} \\ - \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\theta_{CP,q_{CP}^*}, \\ U_{CP}(q_{CP}^*)'' = \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\theta_{CP,q_{CP}^*} \\ - \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}C_{q_{CP}^*}. \end{cases} \tag{29}$$

Since the bidding strategy of content provider should be higher than the transmission cost, the optimization problem for content provider can be described as

$$\text{Problem 1}: \max_{B_{CP}(\theta_{CP,q_{CP}^*})} U_{CP}\left(q_{CP}^*\right)' \quad \text{s.t. } B_{CP}\left(\theta_{CP,q_{CP}^*}\right) \geq C_{q_{CP}^*}. \tag{30}$$

Based on the valuation of content q_{CP}^* for edge server j, the utility function of edge server j can be rewritten as

$$\begin{aligned} U_j\left(q_{CP}^*\right) &= \sum_{i=1}^{N_{i,q}}\sum_{q=1}^{M_{i,q}}\alpha_{i,q}\left(P_{j,q}-C_{j,q}\right) \\ &\quad + \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left(P_{j,q_{CP}^*}-\overline{P_{j,q_{CP}^*}}\right) \\ &= U_j\left(q_{CP}^*\right)' + U_j\left(q_{CP}^*\right)'', \end{aligned} \tag{31}$$

where

$$\begin{cases} U_j(q_{CP}^*)' = \sum_{i=1}^{N_{i,q}}\sum_{q=1}^{M_{i,q}}\alpha_{i,q}\left(P_{j,q}-C_{j,q}\right) \\ + \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left(P_{j,q_{CP}^*}-\theta_{j,q_{CP}^*}\right), \\ U_j(q_{CP}^*)'' = \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left(\theta_{j,q_{CP}^*}-\overline{P_{j,q_{CP}^*}}\right). \end{cases} \tag{32}$$

The bidding strategy of edge server should be lower than the price that mobile user pays to edge server j for obtaining content q_{CP}^*, the optimization problem for edge server j can be obtained by

$$\text{Problem 2}: \max_{B_{CP}(\theta_{CP,q_{CP}^*})} U_j\left(q_{CP}^*\right)'' \quad \text{s.t. } B_j\left(\theta_{j,q_{CP}^*}\right) \leq P_{j,q_{CP}^*}. \tag{33}$$

Definition 1 (Equilibrium Strategy): $\{B_{CP}(\theta_{CP,q_{CP}^*})^*, B_j(\theta_{j,q_{CP}^*})^*\}$ is the optimal bidding strategy of content provider and edge server j, if it satisfies the following conditions for any bidding strategy $\left\{B_{CP}\left(\theta_{CP,q_{CP}^*}\right), B_j\left(\theta_{j,q_{CP}^*}\right)\right\}$: $U_{CP}(q_{CP}^*)'^* \geq U_{CP}(q_{CP}^*)'$ and $U_j(q_{CP}^*)''^* \geq U_j(q_{CP}^*)''$.

Based on the bidding strategy of each player, we have the following cases:

Case 1: If $B_j\left(\theta_{j,q_{CP}^*}\right) < B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$, the transaction between content provider and edge server j will be cancelled and the utility of each player is zero. In this case, mobile user cannot obtain the content (i.e., q_{CP}^*). The content provider needs to reduce the valuation of content and the edge server should increase the valuation of content to reach an agreement.

Case 2: If $B_j\left(\theta_{j,q_{CP}^*}\right) = B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$, the transaction will be ended with the bidding price $B_{CP}\left(\theta_{CP,q_{CP}^*}\right)^*$. In this case, mobile user pays the payment P_{j,q_{CP}^*} to edge server j and the payment $\overline{P_{j,q_{CP}^*}}$ is paid to content provider by edge server j. Both players can obtain utility from the transaction.

Case 3: If $B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$, since each player wants to obtain more utility from the transaction, the equilibrium strategy can be obtained by analyzing the bidding strategy based on the double auction game.

For content provider, substituting (19) into (30), the utility function for case 3 in Problem 1 becomes

$$\begin{aligned} &U_{CP}\left(q_{CP}^*\right)' \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\overline{P_{j,q_{CP}^*}} - \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\theta_{CP,q_{CP}^*} \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left\{\begin{array}{l}\gamma B_j\left(\theta_{j,q_{CP}^*}\right)+(1-\gamma)\times \\ B_{CP}\left(\theta_{CP,q_{CP}^*}\right)-\theta_{CP,q_{CP}^*}\end{array}\right\}. \end{aligned} \tag{34}$$

The expected utility function of content provider can be described as

$$\begin{aligned} &\max_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \mathbb{E}\left\{U_{CP}\left(q_{CP}^*\right)'\right\} \\ &= \max_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left\{\begin{array}{l}\gamma\mathbb{E}\left[B_j\left(\theta_{j,q_{CP}^*}\right)\right] \\ +(1-\gamma)B_{CP}\left(\theta_{CP,q_{CP}^*}\right) \\ -\theta_{CP,q_{CP}^*}\end{array}\right\} \\ &\quad \times \Pr\left\{B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\}, \end{aligned} \tag{35}$$

where $\Pr\left\{B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\}$ indicates the probability that the bidding strategy of edge server j is higher than that of content provider.

For edge server j, substituting (19) into (33), the utility function for case 3 in Problem 2 becomes

$$\begin{aligned} &U_j\left(q_{CP}^*\right)'' \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left(\theta_{j,q_{CP}^*}-\overline{P_{j,q_{CP}^*}}\right) \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*}\left\{\begin{array}{l}\theta_{j,q_{CP}^*}-\gamma B_j\left(\theta_{j,q_{CP}^*}\right) \\ -(1-\gamma)B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\end{array}\right\}. \end{aligned} \tag{36}$$

The expected utility function of edge server j can be calculated by

$$\max_{B_j\left(\theta_{j,q_{CP}^*}\right)} \mathbb{E}\left\{U_j\left(q_{CP}^*\right)''\right\}$$

$$= \max_{B_j\left(\theta_{j,q_{CP}^*}\right)} \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*} \left\{ \begin{array}{l} \theta_{j,q_{CP}^*} - \gamma B_j\left(\theta_{j,q_{CP}^*}\right) - \\ (1-\gamma)\,\mathbb{E}\left[B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right] \end{array} \right\}$$
$$\times \overline{\Pr}\left\{B_{CP}\left(\theta_{CP,q_{CP}^*}\right) < B_j\left(\theta_{j,q_{CP}^*}\right)\right\}, \tag{37}$$

where $\overline{\Pr}\left\{B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\}$ is the probability that the bidding strategy of content provider is lower than that of edge server j.

Let ${V_{q_{CP}^*}}^{\min}$ and ${V_{q_{CP}^*}}^{\max}$ indicate the minimum and maximum valuation of content q_{CP}^*, respectively. θ_{CP,q_{CP}^*} follows the uniform distribution with the interval $\left[C_{q_{CP}^*}, {V_{q_{CP}^*}}^{\max}\right]$, while θ_{j,q_{CP}^*} follows the uniform distribution with the interval $\left[{V_{q_{CP}^*}}^{\min}, P_{j,q_{CP}^*}\right]$. Therefore, the bidding function of content provider and edge server j can be separately expressed as

$$B_{CP}\left(\theta_{CP,q_{CP}^*}\right) = a_{CP} + b_{CP}\theta_{CP,q_{CP}^*}, \tag{38}$$

$$B_j\left(\theta_{j,q_{CP}^*}\right) = a_j + b_j\theta_{j,q_{CP}^*}, \tag{39}$$

where a_{CP} and b_{CP} are the valuation parameters of content provider. a_j and b_j denote the valuation parameters of edge server j.

Theorem 1. For content q_{CP}^*, the optimal bidding strategy of content provider can be given by

$$B_{CP}\left(\theta_{CP,q_{CP}^*}\right)^* = \frac{(1-\gamma)\left(a_j + b_j P_{j,q_{CP}^*}\right) + \theta_{CP,q_{CP}^*}}{2-\gamma}. \tag{40}$$

Proof: Refer to Appendix A.

Theorem 2. For content q_{CP}^*, the optimal bidding strategy of edge server j can be obtained by

$$B_j\left(\theta_{j,q_{CP}^*}\right)^* = \frac{\gamma\left(a_{CP} + b_{CP}C_{q_{CP}^*}\right) + \theta_{j,q_{CP}^*}}{1+\gamma}. \tag{41}$$

Proof: Refer to Appendix B.

Therefore, the equilibrium strategy is obtained in the proposed scheme, which is described as $\{B_{CP}(\theta_{CP,q_{CP}^*})^*, B_j(\theta_{j,q_{CP}^*})^*\}$. Based on the optimal bidding strategy, each player can obtain the maximum utility. The cooperative scheme for content provider and edge server is shown in Algorithm 1.

VI. PERFORMANCE EVALUATIONS

This section reports on simulations to evaluate the performance of the proposed scheme. The simulation setup is first introduced, then the numerical results and analysis are given.

A. SIMULATION SETUP

In the simulation scenario, there is a community consisting of one content provider, 10 edge servers, and 100 mobile users. There are 1000 contents stored in content provider.

Algorithm 1 : Cooperative Scheme for Content Provider and Edge Server

Input: $i \in I, j \in J, q \in Q, s_j \in \left[{s_j}^{\min}, {s_j}^{\max}\right], s_q \in \left[{s_q}^{\min}, {s_q}^{\max}\right], \mu_j, \underline{\mu_{CP}}, \varphi_{k,q_{CP}^*}, \phi_{k,q_{CP}^*}, \gamma$
Output: $P_{j,q_{CP}^*}, \overline{P_{j,q_{CP}^*}}$
Phase 1: The optimal content caching decision
Initialize $Q_j\left(s_j, a_j\right)$
Repeat
  Edge server j determines its current caching state ${s_j}^t$;
  Edge server j selects a content replacement action ${a_j}^t$;
  Edge server j calculates the reward by using (3);
  Update Q-value by using (2);
  ${s_j}^{t+1} \leftarrow {s_j}^t$;
  ${a_j}^{t+1} \leftarrow {a_j}^t$;
Until Q-value converges
Phase 2: The optimal cooperative strategy
for $(i = 1; i \leq I; i++)$ **do**
  if (content q is cached in edge server j) **then**
    Edge server j delivers content q to mobile user i;
    Mobile user i pays payment to edge server j by using (14);
  else
    Edge server j calculates the content requested from content provider by using (8);
    Content provider delivers content q_{CP}^* to mobile user i;
  end if
end for
The optimal payments P_{j,q_{CP}^*} and $\overline{P_{j,q_{CP}^*}}$ are determined in Phase 3;
Phase 3: The optimal bidding strategy for edge server and content provider
for $(j = 1; j \leq J; j++)$ **do**
  Content provider computes the optimal bidding by using (40);
  Edge server j computes the optimal bidding by using (41);
  Mobile user pays the payment P_{j,q_{CP}^*} to edge server j by using (15);
  Edge server j pays the payment $\overline{P_{j,q_{CP}^*}}$ to content provider by using (19);
end for
Return: $P_{j,q_{CP}^*}, \overline{P_{j,q_{CP}^*}}$;

The popularity of each content is determined based on the Zipf distribution with the exponent value 0.5. The contents are cached in edge servers by the content provider based on Q-learning. The learning rate λ and discount factor υ are set to be 0.7 and 0.8, respectively. The maximum transmission rate of content provider is set to be 5Mbps. Other parameters in simulation are given in Table 2 [50], [51].

We compare the proposed scheme with the conventional schemes, which are listed as follows:

TABLE 2. Simulation parameters.

Parameters	Values
$s_j^{\min}, s_j^{\max}$	$\{0.1, 1\}$ Gbytes
$s_q^{\min}, s_q^{\max}$	$\{1, 5\}$ Mbytes
μ_{CP}	$\{1, 2, 3, 4, 5\}$ Mbps
μ_j	1Mbps
ρ_j	0.5
ω_1, ω_2	$\{0.35, 0.30\}$
p_{unit}	0.5
ζ_{unit}	0.1
$\varphi_{1,q_{CP}^*}, \varphi_{2,q_{CP}^*}, \varphi_{3,q_{CP}^*}$	$\{0.1, 0.2, 0.1\}$
$\phi_{1,q_{CP}^*}, \phi_{2,q_{CP}^*}, \phi_{3,q_{CP}^*}$	$\{0.1, 0.2, 0.1\}$
γ	0.5
a_{CP}, b_{CP}	$\{0.05, 0.01\}$
a_j, b_j	$\{0.05, 0.01\}$

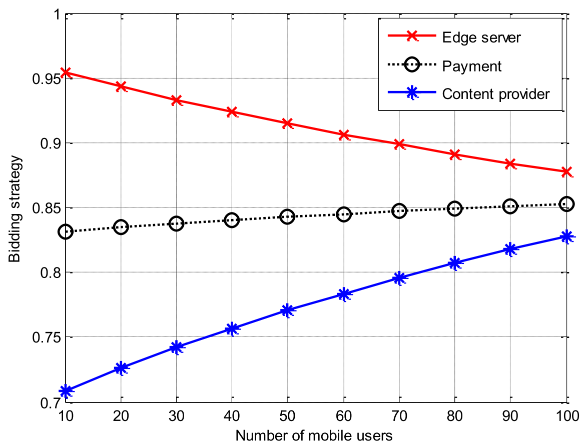


FIGURE 2. The changes of bidding strategy with different number of mobile users.

- The least frequently used (LFU) scheme [52]: In this scheme, the content is eliminated based on the historical request frequency. If a content has been accessed multiple times in the past, the content will be requested more frequently in the future.
- The least recently used (LRU) scheme [53]: In this scheme, the content is eliminated based on the historical request records. If a content has been requested recently, the probability that the content will be requested in the future is high.

B. PERFORMANCE COMPARISON

In this subsection, we first evaluate the bidding strategy (i.e., $B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$, $B_j\left(\theta_{j,q_{CP}^*}\right)$) of the proposed scheme with different parameters. Fig. 2 shows the changes of bidding strategy with different number of mobile users. As we can see that the bidding strategy of content provider increases with the increase of the number of mobile users, while the bidding strategy of edge server decreases. Moreover, the bidding strategy of edge server is higher than that of content provider. The reasons for these are as follows: on one hand, with more mobile users request content, the transmission cost for content provider becomes high, resulting in the high valuation of content. Thus, it brings a high bidding strategy to content provider. On the other hand, the valuation of content for edge server is inversely proportional to the number of mobile users. When the number of mobile users increases, the bidding strategy of edge server decreases.

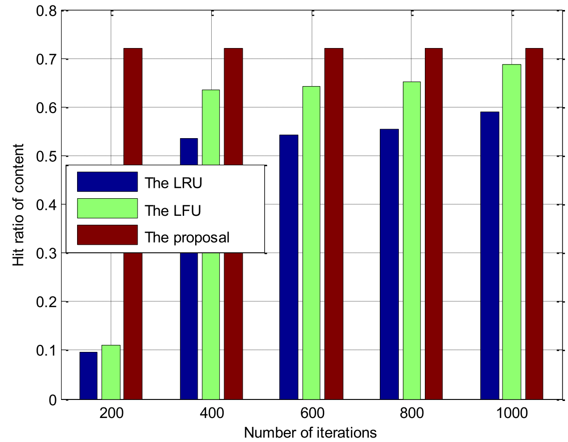


FIGURE 3. The changes of content's hit ratio with different number of iterations.

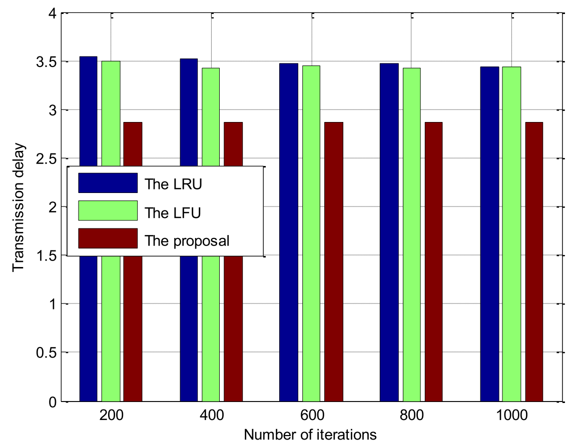


FIGURE 4. The changes of transmission delay with different number of iterations.

Next, we study the performance of the proposed scheme by comparing it with other conventional schemes. Fig. 3 shows the changes of content's hit ratio with different number of iterations. It can be seen that the proposed scheme outperforms the other schemes with different number of iterations. The content's hit ratio increases with the increase of the number of iterations in LFU and LRU. The reasons for these are as follows: the contents are cached in edge servers based on the Q-learning and the reward function is designed based on the gain and loss of caching contents. The optimal content can be cached in each iteration, which leads to a high hit ratio in the proposed scheme. As for the LFU and LRU, when the content request pattern changes, a large number of iterations should be taken to update the request pattern. As a result, the hit ratio in LFU and LRU is lower compared with the proposed scheme.

Fig. 4 shows the changes of transmission delay with different number of iterations. As we can see from Fig. 4, with the

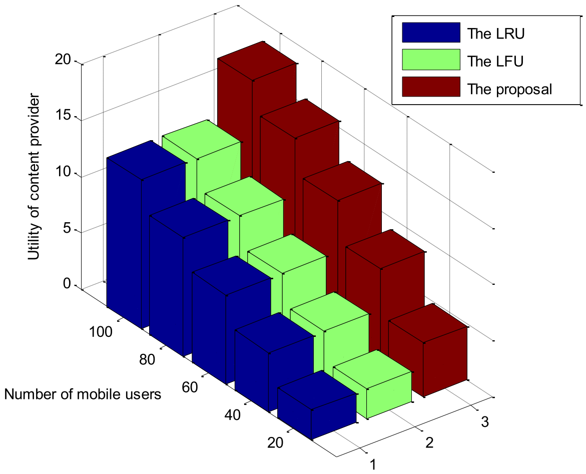


FIGURE 5. The changes of content provider's utility with different number of mobile users.

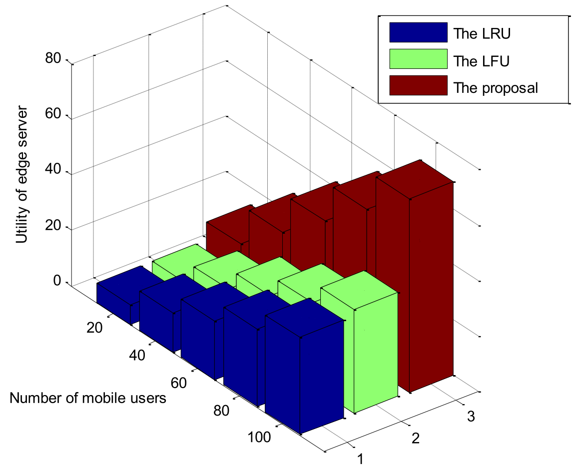


FIGURE 6. The changes of edge server's utility with different number of mobile users.

increase of the number of iterations, the proposed scheme can obtain the lowest transmission delay than other schemes. It is because that the optimal content can be cached in edge server based on the Q-learning. More contents can be delivered to mobile users by edge severs, resulting in the low transmission delay. As for the LFU and LRU, if the content is not cached in edge server, more iterations for content replacement are taken to obtain the objective content. Consequently, the transmission delay is high in the LFU and LRU.

Fig. 5 shows the changes of content provider's utility with different number of mobile users. It can be seen that the proposed scheme can obtain the highest utility for content provider than other schemes. Moreover, with the number of mobile users increases, the utility of content provider increases. The reasons are two-fold: first, with more mobile users request contents, the number of cooperations between content provider and edge server becomes large. Second, the optimal bidding strategy is determined based on the double auction game. Therefore, the proposed scheme can bring high utility to content provider. As for the LFU and LRU, without considering the optimal transaction price, the number of transactions for content provider to deliver content is low, resulting in the low utility for content provider.

Fig. 6 shows the changes of edge server's utility with different number of mobile users. From Fig. 6, we can see that the proposed scheme can achieve the highest utility for edge server compared with other schemes. Moreover, the utility of edge server increases with the increase of the number of mobile users. The reasons for these are as follows: first, with the optimal content caching strategy, the probability that mobile user obtains content from edge server is high. The number of transactions between edge server and mobile users is great. Second, the optimal transaction price is determined based on the double auction game. Third, the cooperative scheme for edge server and content provider can increase the utility of edge server. Consequently, the proposed scheme leads the highest utility to edge server than other schemes.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a cooperative scheme for edge server and content provider to improve the efficiency of content delivery in HetNets. Firstly, the framework with backbone networks and mobile edge networks for content delivery is introduced. Secondly, a Q-learning based scheme for content caching is proposed to cache the optimal content in edge servers. Thirdly, to improve the QoE of mobile user, the cooperative scheme for content delivery between edge server and content provider is modeled as the double auction game based incentive. The equilibrium strategy is derived by analyzing the bidding strategy. Finally, the performance of the proposed scheme is evaluated through simulations. The simulation results demonstrate that the proposed scheme can jointly improve the efficiency of content delivery and bring more utility for edge server and content provider compared with the conventional schemes.

In the future work, we plan to expand this work from the following aspects: first, we expect to study the security content delivery scheme for edge server and remote server to further improve the reliability of content. Second, we pay attention to design an energy-efficient scheme for HetNets to reduce the cost of content delivery.

APPENDIX A
PROOF OF THEOREM 1

Given the bidding strategy of content provider (i.e., θ_{CP,q_{CP}^*}), the probability that the bidding strategy of edge server j is higher than that of content provider can be calculated by

$$\begin{aligned}
&\Pr\left\{B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\} \\
&\quad = \Pr\left\{a_j + b_j\theta_{j,q_{CP}^*} > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\} \\
&\quad = \frac{a_j + b_j P_{j,q_{CP}^*} - B_{CP}\left(\theta_{CP,q_{CP}^*}\right)}{b_j\left(P_{j,q_{CP}^*} - V_{q_{CP}^*}{}^{\min}\right)}. \qquad (42)
\end{aligned}$$

The bidding strategy $B_j\left(\theta_{j,q_{CP}^*}\right)$ of edge server j follows the uniform distribution in the interval $[a_j + b_j V_{q_{CP}^*}{}^{\min}, a_j + b_j P_{j,q_{CP}^*}]$. The probability density function of $B_j\left(\theta_{j,q_{CP}^*}\right)$ can be obtained by

$$f_j\left[B_j\left(\theta_{j,q_{CP}^*}\right)\right] = \frac{1}{b_j\left(P_{j,q_{CP}^*} - V_{q_{CP}^*}{}^{\min}\right)}. \tag{43}$$

Therefore, the expected bidding strategy of edge server j becomes

$$\begin{aligned} &\mathbb{E}\left[B_j\left(\theta_{j,q_{CP}^*}\right) \middle| B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right] \\ &= \frac{\int_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)}^{a_j+b_jP_{j,q_{CP}^*}} f_j\left[B_j\left(\theta_{j,q_{CP}^*}\right)\right] x dx}{\Pr\left\{B_j\left(\theta_{j,q_{CP}^*}\right) > B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right\}} \\ &= \frac{\int_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)}^{a_j+b_jP_{j,q_{CP}^*}} x dx}{a_j + b_j P_{j,q_{CP}^*} - B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \\ &= \frac{1}{2}\left[a_j + b_j P_{j,q_{CP}^*} + B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right]. \end{aligned} \tag{44}$$

Substituting (42), (44) into (35), we can obtain

$$\begin{aligned} &\max_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \mathbb{E}\left\{U_{CP}(q_{CP}^*)'\right\} \\ &= \max_{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*} \left\{\begin{array}{l} \frac{\gamma}{2}\left[a_j + b_j P_{j,q_{CP}^*}\right] + \\ \frac{\gamma}{2}\left[B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right] + \\ (1-\gamma) B_{CP}\left(\theta_{CP,q_{CP}^*}\right) \\ -\theta_{CP,q_{CP}^*} \end{array}\right\} \\ &\quad \times \frac{a_j + b_j P_{j,q_{CP}^*} - B_{CP}\left(\theta_{CP,q_{CP}^*}\right)}{b_j\left(P_{j,q_{CP}^*} - V_{q_{CP}^*}{}^{\min}\right)}. \end{aligned} \tag{45}$$

The first-order derivative of $\mathbb{E}\left\{U_{CP}(q_{CP}^*)'\right\}$ with respect to $B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$ is

$$\begin{aligned} &\frac{\partial \mathbb{E}\left\{U_{CP}(q_{CP}^*)'\right\}}{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)} \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*} \left\{\begin{array}{l} \frac{(1-\gamma)\left(a_j + b_j P_{j,q_{CP}^*}\right)}{b_j\left(P_{j,q_{CP}^*} - V_{q_{CP}^*}{}^{\min}\right)} + \\ \frac{(\gamma-2) B_{CP}\left(\theta_{CP,q_{CP}^*}\right) + \theta_{CP,q_{CP}^*}}{b_j\left(P_{j,q_{CP}^*} - V_{q_{CP}^*}{}^{\min}\right)} \end{array}\right\}. \end{aligned} \tag{46}$$

Let $\frac{\partial \mathbb{E}\left\{U_{CP}(q_{CP}^*)'\right\}}{B_{CP}\left(\theta_{CP,q_{CP}^*}\right)}$ be equal to zero, we have the optimal bidding strategy of content provider as

$$B_{CP}\left(\theta_{CP,q_{CP}^*}\right)^* = \frac{(1-\gamma)\left(a_j + b_j P_{j,q_{CP}^*}\right) + \theta_{CP,q_{CP}^*}}{2-\gamma}. \tag{47}$$

This completes our proof.

APPENDIX B
PROOF OF THEOREM 2

Given the bidding strategy of edge server j (i.e., θ_{j,q_{CP}^*}), the probability that the bidding strategy of content provider is lower than that of edge server j can be expressed as

$$\begin{aligned} &\overline{\Pr}\left\{B_{CP}\left(\theta_{CP,q_{CP}^*}\right) < B_j\left(\theta_{j,q_{CP}^*}\right)\right\} \\ &= \overline{\Pr}\left\{a_{CP} + b_{CP}\theta_{CP,q_{CP}^*} < B_j\left(\theta_{j,q_{CP}^*}\right)\right\} \\ &= \frac{B_j\left(\theta_{j,q_{CP}^*}\right) - a_{CP} - b_{CP} C_{q_{CP}^*}}{b_{CP}\left(V_{q_{CP}^*}{}^{\max} - C_{q_{CP}^*}\right)}. \end{aligned} \tag{48}$$

The bidding strategy $B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$ of content provider follows the uniform distribution in the interval $[a_{CP} + b_{CP} C_{q_{CP}^*}, a_{CP} + b_{CP} V_{q_{CP}^*}{}^{\max}]$. The probability density function of $B_{CP}\left(\theta_{CP,q_{CP}^*}\right)$ can be calculated by

$$f_{CP}\left[B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right] = \frac{1}{b_{CP}\left(V_{q_{CP}^*}{}^{\max} - C_{q_{CP}^*}\right)}. \tag{49}$$

Therefore, the expected bidding strategy of content provider becomes

$$\begin{aligned} &\mathbb{E}\left[B_{CP}\left(\theta_{CP,q_{CP}^*}\right) \middle| B_{CP}\left(\theta_{CP,q_{CP}^*}\right) < B_j\left(\theta_{j,q_{CP}^*}\right)\right] \\ &= \frac{\int_{a_{CP}+b_{CP}C_{q_{CP}^*}}^{B_j\left(\theta_{j,q_{CP}^*}\right)} f_{CP}\left[B_{CP}\left(\theta_{CP,q_{CP}^*}\right)\right] x dx}{\overline{\Pr}\left\{B_{CP}\left(\theta_{CP,q_{CP}^*}\right) < B_j\left(\theta_{j,q_{CP}^*}\right)\right\}} \\ &= \frac{\int_{a_{CP}+b_{CP}C_{q_{CP}^*}}^{B_j\left(\theta_{j,q_{CP}^*}\right)} x dx}{B_j\left(\theta_{j,q_{CP}^*}\right) - a_{CP} - b_{CP} C_{q_{CP}^*}} \\ &= \frac{1}{2}\left[B_j\left(\theta_{j,q_{CP}^*}\right) + a_{CP} + b_{CP} C_{q_{CP}^*}\right]. \end{aligned} \tag{50}$$

Substituting (48), (50) into (37), we have

$$\begin{aligned} &\max_{B_j\left(\theta_{j,q_{CP}^*}\right)} \mathbb{E}\left\{U_j(q_{CP}^*)''\right\} \\ &= \max_{B_j\left(\theta_{j,q_{CP}^*}\right)} \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*} \left\{\begin{array}{l} \theta_{j,q_{CP}^*} - \gamma B_j\left(\theta_{j,q_{CP}^*}\right) \\ -\frac{(1-\gamma)}{2}\left[B_j\left(\theta_{j,q_{CP}^*}\right)\right] \\ -\frac{(1-\gamma)}{2}\left[a_{CP} + b_{CP} C_{q_{CP}^*}\right] \end{array}\right\} \\ &\quad \times \frac{B_j\left(\theta_{j,q_{CP}^*}\right) - a_{CP} - b_{CP} C_{q_{CP}^*}}{b_{CP}\left(V_{q_{CP}^*}{}^{\max} - C_{q_{CP}^*}\right)}, \end{aligned} \tag{51}$$

The first-order derivative of $\mathbb{E}\left\{U_j(q_{CP}^*)''\right\}$ with respect to $B_j\left(\theta_{j,q_{CP}^*}\right)$ is

$$\begin{aligned} &\frac{\partial \mathbb{E}\left\{U_j(q_{CP}^*)''\right\}}{\partial B_j\left(\theta_{j,q_{CP}^*}\right)} \\ &= \sum_{i=1}^{N_{i,q_{CP}^*}} \beta_{i,q_{CP}^*} \left\{\begin{array}{l} \frac{\gamma\left(a_{CP} + b_{CP} C_{q_{CP}^*}\right) + \theta_{j,q_{CP}^*}}{b_{CP}\left(V_{q_{CP}^*}{}^{\max} - C_{q_{CP}^*}\right)} \\ -\frac{(1+\gamma) B_j\left(\theta_{j,q_{CP}^*}\right)}{b_{CP}\left(V_{q_{CP}^*}{}^{\max} - C_{q_{CP}^*}\right)} \end{array}\right\}. \end{aligned} \tag{52}$$

Let $\frac{\partial \mathbb{E}\left\{U_j(q_{CP}^*)''\right\}}{\partial B_j\left(\theta_{j,q_{CP}^*}\right)}$ be equal to zero, we have the optimal bidding strategy of edge server j as

$$B_j\left(\theta_{j,q_{CP}^*}\right)^* = \frac{\gamma\left(a_{CP} + b_{CP} C_{q_{CP}^*}\right) + \theta_{j,q_{CP}^*}}{1+\gamma}. \tag{53}$$

This completes our proof.

REFERENCES

[1] Y. Xu and F. Liu, "Qos provisionings for device-to-device content delivery in cellular networks," *IEEE Trans. Multimedia*, vol. 19, no. 11, pp. 2597–2608, Nov. 2017.

[2] Z. Su, Q. Xu, and Q. Qi, "Big data in mobile social networks: A QoE-oriented framework," *IEEE Netw.*, vol. 30, no. 1, pp. 52–57, Jan./Feb. 2016.

[3] Q. Xu, Z. Su, K. Zhang, P. Ren, and X. S. Shen, "Epidemic information dissemination in mobile social networks with opportunistic links," *IEEE Trans. Emerg. Topics Comput.*, vol. 3, no. 3, pp. 399–409, Sep. 2015.

[4] Y. Wang, Z. Su, Q. Xu, T. Yang, and N. Zhang, "A novel charging scheme for electric vehicles with smart communities in vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 8487–8501, Sep. 2019. doi: 10.1109/TVT.2019.2923851.

[5] R. Xing, Z. Su, N. Zhang, Y. Peng, H. Pu, and J. Luo, "Trust-evaluation-based intrusion detection and reinforcement learning in autonomous driving," *IEEE Netw.*, vol. 33, no. 5, pp. 54–60, Sep. 2019.

[6] H. Peng, L. Liang, X. Shen, and G. Y. Li, "Vehicular communications: A network layer perspective," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1064–1078, Feb. 2019.

[7] A. Ahmad, A. Paul, M. Khan, S. Jabbar, M. M. U. Rathore, N. Chilamkurti, and N. Min-Allah, "Energy efficient hierarchical resource management for mobile cloud computing," *IEEE Trans. Sustain. Comput.*, vol. 2, no. 2, pp. 100–112, Apr./Jun. 2017.

[8] H. Peng, Q. Ye, and X. S. Shen, "SDN-based resource management for autonomous vehicular networks: A multi-access edge computing approach," *IEEE Wireless Commun.*, vol. 26, no. 4, pp. 156–162, Aug. 2019.

[9] M. Mahdian and E. M. Yeh, "Throughput and delay scaling of content-centric ad hoc and heterogeneous wireless networks," *IEEE/ACM Trans. Netw.*, vol. 25, no. 5, pp. 3030–3043, Oct. 2017.

[10] H. Peng, Q. Ye, and X. Shen, "Spectrum management for multi-access edge computing in autonomous vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, to be published.

[11] Y. Zhou, F. R. Yu, J. Chen, and Y. Kuo, "Resource allocation for information-centric virtualized heterogeneous networks with in-network caching and mobile edge computing," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11339–11351, Dec. 2017.

[12] Z. Su, Y. Hui, and T. H. Luan, "Distributed task allocation to enable collaborative autonomous driving with network softwarization," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 10, pp. 2175–2189, Oct. 2018.

[13] W. Quan, N. Cheng, M. Qin, H. Zhang, H. A. Chan, and X. Shen, "Adaptive transmission control for software defined vehicular networks," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 653–656, Jun. 2019.

[14] X. Li, X. Wang, K. Li, Z. Han, and V. C. M. Leung, "Collaborative multi-tier caching in heterogeneous networks: Modeling, analysis, and design," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6926–6939, Oct. 2017.

[15] W. Quan, Y. Liu, H. Zhang, and S. Yu, "Enhancing crowd collaborations for software defined vehicular networks," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 80–86, Aug. 2017.

[16] C. Ma, M. Ding, H. Chen, Z. Lin, G. Mao, Y. Liang, and B. Vucetic, "Socially aware caching strategy in device-to-device communication networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4615–4629, May 2018.

[17] L. Zhou, D. Wu, Z. Dong, and X. Li, "When collaboration hugs intelligence: Content delivery over ultra-dense networks," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 91–95, Dec. 2017.

[18] M. Taghizadeh, K. Micinski, C. Ofria, E. Torng, and S. Biswas, "Distributed cooperative caching in social wireless networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 6, pp. 1037–1053, Jun. 2013.

[19] J. Song, M. Sheng, T. Q. S. Quek, C. Xu, and X. Wang, "Learning-based content caching and sharing for wireless networks," *IEEE Trans. Commun.*, vol. 65, no. 10, pp. 4309–4324, Oct. 2017.

[20] W. Jiang, G. Feng, S. Qin, T. S. P. Yum, and G. Cao, "Multi-agent reinforcement learning for efficient content caching in mobile D2D networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 3, pp. 1610–1622, Mar. 2019.

[21] N. Cheng, F. Lyu, W. Quan, C. Zhou, H. He, W. Shi, and X. Shen, "Space/aerial-assisted computing offloading for IoT applications: A learning-based approach," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 5, pp. 1117–1129, May 2019.

[22] D. Zhang, Y. Qiao, L. She, R. Shen, J. Ren, and Y. Zhang, "Two time-scale resource management for green Internet of Things networks," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 545–556, Feb. 2019.

[23] Y. Wang, Z. Su, and N. Zhang, "BSIS: Blockchain-based secure incentive scheme for energy delivery in vehicular energy network," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3620–3631, Jun. 2019. doi: 10.1109/TII.2019.2908497.

[24] L. Zhang, Z. Wang, M. Xiao, G. Wu, Y.-C. Liang, and S. Li, "Decentralized caching schemes and performance limits in two-layer networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 12177–12192, Dec. 2018.

[25] D. Zhang, Z. Chen, M. K. Awad, N. Zhang, H. Zhou, and X. S. Shen, "Utility-optimal resource management and allocation algorithm for energy harvesting cognitive radio sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3552–3565, Dec. 2016.

[26] L. Xiang, D. W. K. Ng, R. Schober, and V. W. S. Wong, "Cache-enabled physical layer security for video streaming in backhaul-limited cellular networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 2, pp. 736–751, Feb. 2018.

[27] D. Zhang, L. Tan, J. Ren, M. K. Awad, S. Zhang, Y. Zhang, and P. Wan, "Near-optimal and truthful online auction for computation offloading in green edge-computing systems," *IEEE Trans. Mobile Comput.*, to be published.

[28] H. T. Nguyen, H. D. Tuan, T. Q. Duong, H. V. Poor, and W.-J. Hwang, "Collaborative multicast beamforming for content delivery by cache-enabled ultra dense networks," *IEEE Trans. Commun.*, vol. 67, no. 5, pp. 3396–3406, May 2019.

[29] W. Jiang, G. Feng, and S. Qin, "Optimal cooperative content caching and delivery policy for heterogeneous cellular networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 5, pp. 1382–1393, May 2017.

[30] L. Al-Kanj, Z. Dawy, W. Saad, and E. Kutanoglu, "Energy-aware cooperative content distribution over wireless networks: Optimized and distributed approaches," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3828–3847, Oct. 2013.

[31] J. Sung, M. Kim, K. Lim, and J.-K. K. Rhee, "Efficient cache placement strategy in two-tier wireless content delivery network," *IEEE Trans. Multimedia*, vol. 18, no. 6, pp. 1163–1174, Jun. 2016.

[32] Z. Qin, X. Gan, L. Fu, X. Di, J. Tian, and X. Wang, "Content delivery in cache-enabled wireless evolving social networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 10, pp. 6749–6761, Oct. 2018.

[33] Y. Ma and A. Jamalipour, "A cooperative cache-based content delivery framework for intermittently connected mobile ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 366–373, Jan. 2010.

[34] O. Ayoub, F. Musumeci, M. Tornatore, and A. Pattavina, "Energy-efficient video-on-demand content caching and distribution in metro area networks," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 1, pp. 159–169, Mar. 2019.

[35] J. Xie, R. Xie, T. Huang, J. Liu, and Y. Liu, "ICICD: An efficient content distribution architecture in mobile cellular network," *IEEE Access*, vol. 5, pp. 3205–3215, 2017.

[36] S. H. Chae, T. Q. S. Quek, and W. Choi, "Content placement for wireless cooperative caching helpers: A tradeoff between cooperative gain and content diversity gain," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6795–6807, Oct. 2017.

[37] H. Nishiyama, H. Yamada, H. Yoshino, and N. Kato, "A cooperative user-system approach for optimizing performance in content distribution/delivery networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 2, pp. 476–483, Feb. 2012.

[38] S. Jia, C. Xu, J. Guan, H. Zhang, and G.-M. Muntean, "A novel cooperative content fetching-based strategy to increase the quality of video delivery to mobile users in wireless networks," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 370–384, Jun. 2014.

[39] F.-Z. Jiang, K. Thilakarathna, S. Mrabet, M. A. Kaafar, and A. Seneviratne, "uStash: A novel mobile content delivery system for improving user QoE in public transport," *IEEE Trans. Mobile Comput.*, vol. 18, no. 6, pp. 1447–1460, Jun. 2019.

[40] Z. Xiong, S. Feng, D. Niyato, P. Wang, A. Leshem, and Z. Han, "Joint sponsored and edge caching content service market: A game-theoretic approach," *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 1166–1181, Feb. 2019.

[41] B. Barua, Z. Khan, Z. Han, A. A. Abouzeid, and M. Latva-Aho, "Incentivizing selected devices to perform cooperative content delivery: A carrier aggregation-based approach," *IEEE Trans. Wireless Commun.*, vol. 15, no. 7, pp. 5030–5045, Jul. 2016.

[42] M.-J. Shih, T.-H. Wu, and H.-Y. Wei, "Unlicensed LTE pricing for tiered content delivery and heterogeneous user access," *IEEE Trans. Mobile Comput.*, vol. 18, no. 1, pp. 235–249, Jan. 2019.

[43] C. Xu, J. Feng, Z. Zhou, J. Wu, and C. Perera, "Cross-layer optimization for cooperative content distribution in multihop device-to-device networks," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 278–287, Feb. 2019.

[44] N. Kumar, N. Chilamkurti, and J. J. P. C. Rodrigues, "Bayesian coalition game as-a-service for content distribution in Internet of vehicles," *IEEE Internet Things J.*, vol. 1, no. 6, pp. 544–555, Dec. 2014.

[45] X. Zhang and B. Li, "On the market power of network coding in P2P content distribution systems," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 12, pp. 2063–2070, Dec. 2011.

[46] R. Lu, X. Lin, Z. Shi, and J. Shao, "PLAM: A privacy-preserving framework for local-area mobile social networks," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, Apr./May 2014, pp. 763–771.

[47] R. Liu, J. Liang, J. Cao, K. Zhang, W. Gao, L. Yang, and R. Yu, "Understanding mobile users' privacy expectations: A recommendation-based method through crowdsourcing," *IEEE Trans. Services Comput.*, vol. 12, no. 2, pp. 304–318, Mar./Apr. 2019.

[48] G. Alfano, M. Garetto, and E. Leonardi, "Content-centric wireless networks with limited buffers: When mobility hurts," *IEEE/ACM Trans. Netw.*, vol. 24, no. 1, pp. 299–311, Feb. 2016.

[49] K. Xue, P. He, X. Zhang, Q. Xia, D. S. L. Wei, H. Yue, and F. Wu, "A secure, efficient, and accountable edge-based access control framework for information centric networks," *IEEE/ACM Trans. Netw.*, vol. 27, no. 3, pp. 1220–1233, Jun. 2019.

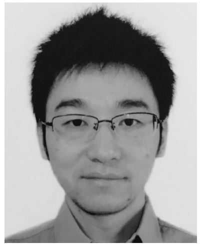
[50] D. Tuncer, V. Sourlas, M. Charalambides, M. Claeys, J. Famaey, G. Pavlou, and F. De Turck, "Scalable cache management for ISP-operated content delivery services," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 8, pp. 2063–2076, Aug. 2016.

[51] S. M. Azimi, O. Simeone, A. Sengupta, and R. Tandon, "Online edge caching and wireless delivery in fog-aided networks with dynamic content popularity," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 6, pp. 1189–1202, Jun. 2018.

[52] G. Ma, Z. Wang, M. Zhang, J. Ye, M. Chen, and W. Zhu, "Understanding performance of edge content caching for mobile video streaming," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 5, pp. 1076–1089, May 2017.

[53] H. Gomaa, G. G. Messier, and R. Davies, "Hierarchical cache performance analysis under TTL-based consistency," *IEEE/ACM Trans. Netw.*, vol. 23, no. 4, pp. 1190–1201, Aug. 2015.

MINGHUI DAI is currently pursuing the Ph.D. degree with the School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China. His research interests include wireless network architecture and vehicular networks.



ZHOU SU received the Ph.D. degree from Waseda University, Tokyo, Japan, in 2003. His research interests include multimedia communication, wireless communication, and network traffic. He is a TPC Member of some flagship conferences, including the IEEE INFOCOM, the IEEE ICC, and the IEEE GLOBECOM. He received the Best Paper Award of the International Conference CHINACOM2008 and the Funai Information Technology Award for Young Researchers, in 2009. He is the Chair of the Multimedia Services and Applications over Emerging Networks Interest Group (MENIG) of the IEEE Comsoc Society's Multimedia Communications Technical Committee. He also served as the Co-Chair for several international conferences, including the IEEE VTC Spring 2016 and IEEE CCNC2011. He is an Associate Editor of *IET Communications* and the *IEICE Transactions on Communications*.

QICHAO XU received the Ph.D. degree from the School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China, in 2019, where he is currently an Assistant Professor. His research interests include wireless network architecture and vehicular networks.

WEIWEI CHEN is currently pursuing the master's degree with the School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China. His research interests include wireless network architecture and vehicular networks.

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