Secure Content Delivery With Edge Nodes to Save Caching Resources for Mobile Users in Green Cities

Qichao Xu, Zhou Su, Qinghua Zheng, Minnan Luo, and Bo Dong

***Abstract*—To save energy during content delivery in green cities, caching contents on edge nodes that are placed near mobile social users has been advocated recently. However, how to allocate the limited caching resources with secure content delivery becomes a new challenge. Therefore, in this paper, we present a novel theoretical model to deliver secure content with edge nodes in order to save energy for green cities. First, we present a reverse auction game to encourage edge nodes to cooperatively provide caching services with incentives. With the model, mobile users can determine the candidate of edge node to cache content based on the interaction between mobile users and edge nodes. Second, a trust management method is designed to evaluate the reliability of the selected candidate of edge node by considering the direct trust evaluation. Finally, extensive simulations show that the proposal can save energy with a secure content delivery where both the delay to obtain the content and the caching ratio can be improved compared with the conventional methods.**

***Index Terms*—Content delivery, edge computing, energy, green cities, reverse auction game.**

I. Introduction

With the fast development of information technologies and rapid growth of population of network users, energy informatics has emerged to efficiently tackle energy-aware issues such as global warming, energy crisis, and climate change challenges. A recent report shows that the number of mobile devices connected to the Internet has been more than the population in the world since 2014 [1]. The population in the cities has increased rapidly in the last decade due to the increasing rate of urbanization. The green city is aimed to efficiently utilize the energy to keep the sustainable development of environment. Due to the limited resources of energy and the ever increasing demands of energy, it poses a new challenge to build green cities in future days, in which the energy should be efficiently allocated and saved in order to provide users with a satisfactory quality of experiences.

Toward green cities, mobile users with the common interests may form communities in the mobile social networks (MSNs) [2]–[5] to exchange and share contents with each other. Mobile users in the MSNs can not only request contents from others, but also generate contents by themselves. As these contents such as video and audio have a large data size, to deliver content among a large number of mobile users in MSNs by mobile devices may consume a huge amount of energy [6]–[8]. Besides, the contents need to be delivered to multiple users in different sites where the security problems should be considered. For example, receiving content from mobile social users who are not trustworthy may bring viruses. Therefore, it becomes an important issue for mobile users in green cities to deliver content efficiently where the content should be securely delivered with the satisfactory user delay and network load balance.

Mobile edge computing has emerged as a promising solution that can provide computing and caching service to mobile users. Caching content on edge nodes has been advocated to resolve the above issues with the following reasons. On one hand, edge nodes are placed near mobile social users in MSNs. Compared to the existing solutions to fetch content from the remote server, the content requested by mobile users can be directly provided by a nearby edge node. As a result, from the view of the networks, the energy for the networks to deliver content from remote server can be saved [9]–[11]. On the other hand, the delay to obtain content for users is reduced as the cached content in edge nodes can be provided.

However, the large-scale deployment of edge caching in green cities in reality faces several fundamental problems. First, as the caching capacity of each edge node is limited, how to allocate the caching resources to save energy during content delivery should be studied. Second, the trust of mobile social users should be considered to deliver content based on the social tie. For example, some users are warm-hearted to contribute content

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while part of users may be malicious to spread virus to others. Although some existed works [12]–[14] have made efforts for caching in mobile networks, most of them focus on the edge caching to optimize the cache hit ratio, where the social features of mobile users and the security considerations for edge nodes have not been discussed enough. Therefore, it is an open and important issue to design a secure content delivery for green cities.

In this paper, we present a novel scheme to securely deliver content for mobile users by edge nodes to save energy in green cities. First, in order to encourage the edge nodes to cooperatively provide caching services, we introduce a reverse auction game model with incentives for edge node. Based on the interaction between mobile users and edge nodes, the candidate of edge node can be selected by mobile users to cache content with the bid containing the caching price and caching size. Second, we present a trust management method to evaluate the security of the candidate of edge node. The direct trust evaluation is considered to determine whether to cache content in the selected candidate of the edge node. Finally, the extensive simulations show that the proposal outperforms the existing schemes with the low delay and high secure caching ratio.

The remainder of this paper is as follows. Section II shows related work. Section III presents the system model. Section IV introduces the proposed scheme. Section V shows the performance evaluation of the proposed scheme, and the Section VI closes this work with conclusions.

II. Related Work

A. Energy Informatics for Green Cities

Lamaina *et al.* [15] presented an exhaustive search scheme for the optimal placement of wind turbines in electrical distribution systems. The wind speed, the load demand uncertainty, and the variability of electrical energy prices are considered to improve the distribution network acquisition market. Yin *et al.* [16] studied a utility function-based real-time control for a battery-ultracapacitor hybrid energy system. The packs are modeled as two independent agents to represent different performance and requirements of the battery and ultracapacitor. Bessa *et al.* [17] presented a new vector autoregression framework based spatial temporal forecasting scheme. It can observe the solar generation collected by smart meters and distribution transformer controllers. However, few of them consider the energy consumption of network backbone, which may need a large amount of energy to deliver information.

B. Content Delivery in Mobile Networks

Li *et al.* [18] studied the space-crossing community detection and data forwarding in MSNs. The authors propose a framework to construct the hybrid underlying network with access point to support data forwarding and the base stations to load off the traffic. Hu *et al.* [19] proposed a cooperative-social-multicast-protocol-aided content dissemination scheme based on a self-organized ad hoc network. The model is presented to study the process of content dissemination by Markov chain. Xia *et al.* [20] proposed a signaling game approach to improve data forwarding with the cooperation among well-behaved nodes and selfish nodes. However, how to securely deliver content with the edge computing in MSNs is not sufficiently discussed. Especially, the trustworthy content delivery between edge node and mobile users should be discussed in detail.

C. Caching Contents in Wireless Networks

Zhu *et al.* [21] studied the cost of caching with the consideration of social ties and physical distance. The authors propose a social-aware caching game to encourage nodes to cache data with incentives. Wang *et al.* [22] proposed a Markov chain-based model to cache contents among edge nodes. Content sharing among MSNs with fog radio access networks is also studied. Zhang *et al.* [23] studied the caching methods for a two-layer social cyberspace. Based on the traffic correlation between base stations and social relationship among user equipments, social users with common interest can share contents which are cached. However, most of them assume that all users are secure and honest, where the trust of users should be studied.

D. 5G Communication for Content Caching

Qiao *et al.* [24] proposed a caching-based millimeter wave framework in 5G networks by precaching video contents at the base station for handoff users, where the connection and retrieval delays are significantly reduced. Malark *et al.* [25] derived the probability of successful content delivery in the presence of interference and noise with stochastic geometry for device-to-device communication. The users can cache multiple files and different cached files can be transmitted simultaneously throughout the network. Tran *et al.* [26] designed a novel cooperative hierarchical caching framework in 5G cloud radio access network where contents are jointly cached. Poularakis *et al.* [27] presented a network paradigm toward next-generation cellular networks, to satisfy the explosive demand for mobile data while minimizing energy expenditures by caching and multicast popular contents. However, the security for caching contents in 5G communication is not sufficiently discussed in these works.

III. System Model

In this section, we describe the system model of the presented scheme in detail. The network model shown in Fig. 1 is introduced at first. Then, the content model and security model are elaborated.

A. Network Model

The network model can be classified into three parts as follows.

1) *Cloud Server:* A cloud server is placed by the authorities such as network operators, governments, etc., to store contents for mobile users. As mobile users are located far away from the server, it causes a delay to obtain content from the server for mobile users. Here, it needs κ route nodes in backbone network to fetch the content from the cloud server. The cloud server can provide a secure and

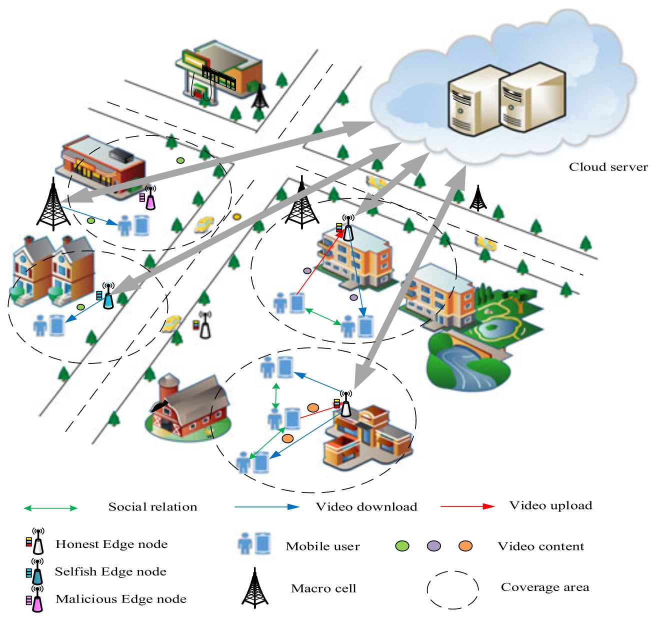

Fig. 1. System model.

trustworthy content service. The bandwidth between two connected route nodes is denoted as ϱ. Then, the delay to deliver content per unit of data size in the backbone network becomes

$$d = \frac{1}{\varrho} \cdot (\kappa + 1). \tag{1}$$

Here, both the bandwidth between the access point and route node, and the bandwidth between cloud server and route node are ϱ.

2) *Edge node:* There are a group of edge nodes, which are placed between the cloud server and mobile users. The edge node is an Internet-connected computer or server which is located at the edge of the content provider's backbone. Compared to the cloud sever, the edge node is much closer to mobile users. Due to the limited caching capacity, an edge node can store some selective contents. Let $\mathcal{I} = \{1 \ldots, i, \ldots, I\}$ denote the set of edge nodes in an area such as a campus, an office building, and a park. The maximum wireless bandwidth provided for one mobile user by edge node i is denoted as b_i and the maximum number of concurrent users for an edge node i to be allowed is n_i. With the short range wireless communication, mobile users can access the edge node to cache or deliver contents. Due to the limited coverage, the edge node has a limited radius of coverage, which is denoted by R_i for edge node i. Let $l_{i,j}$ denote the distance between edge node i and mobile user j . S_i denotes the spare capacity of edge node i. The number of mobile users to access an edge node i follows a Poission distribution with the parameter λ_i. In addition, the service time of each edge node follows the exponential distribution and the average service rate for each mobile user is μ_i. Therefore, the average number of concurrent mobile users for accessing services from edge node i becomes

$$\mathrm{AC}_i = \sum_{k=1}^{n_i} \left(k \cdot {\rho_i}^k \Big/ \left(k! \sum_{l=0}^{n_i} \frac{{\rho_i}^l}{l!} \right) + 0 \cdot \left(\sum_{k=0}^{n_i} \frac{{\rho_i}^k}{k!} \right)^{-1} \right. \tag{2}$$

where $\rho_i = \lambda_i / \mu_i$. The edge nodes can cooperatively provide contents to mobile users. When the users move from the coverage area of one edge node to another edge node, the interested contents can be delivered to the edge node in previous.

3) *Mobile users:* Different from other networks, mobile users in an MSN are not only contents consumers, but also the generators of contents. Specifically, if a mobile user finds or generates an interesting content, this user can upload the content to the cloud server or the edge node and recommend this content to his/her friends with a link via social platforms (e.g., Facebook, Wechat, QQ, etc.). Indeed, the mobile users with social relations usually have the similar interests. Thus, mobile users have high will to watch the contents shared by their friends. Let $\mathcal{J} = \{1, 2, \ldots, j, \ldots, J\}$ be the set of mobile users in the networks. For any two mobile users, the social relation degree is denoted as $r_{j,j'}$ $(j \in \mathcal{J},\ j' \in \mathcal{J})$, where $0 \leq r_{j,j'} \leq 1$. $r_{j,j'} = 1$ means two mobile users j, j' have the highest social relation, while $r_{j,j'} = 0$ means two mobile users j and j' have no relation. The frequency of contact between two users has the effect on the direct interactions to evaluate the social relation. Therefore, we can use the historical interaction data to calculate the social relation between two mobile users by

$$r_{j,j'} = \frac{t_{\widehat{j,j'}}}{\max\{t_{\widehat{j,j'}}\}}, \quad j, j' \in \mathcal{J} \tag{3}$$

where $t_{\widehat{j,j'}}$ is the number of interactions between mobile user j and mobile user j' within a period.

B. Content Model

We consider a constant bitrate streaming video model, as it is an adaptive one which can support different mobile devices to have different features to generate contents. For storing a content, the source file of content is partitioned into multiple segments and then delivered to mobile users. Each segment is corresponding to a short playback time (e.g., 2–10 s) of the content, where users can download the content segment by segment. $\hat{l}_j$ denotes the segment length of mobile user j's content. The bitrate of the content generated by mobile user j is denoted as bt_j. If a content of mobile user j has L_j seconds, the data size of this content becomes

$$D_j = L_j \cdot bt_j. \tag{4}$$

Here, a unit of segment length for all users' contents is assumed, i.e., $\hat{l}_j = 1$ s, $\forall j \in \mathcal{J}$. In MSNs, mobile users can not only request contents from others, but also can generate contents by themselves. Especially, the mobile users who have generated contents can share contents with their friends by a link. For a given content, the mobile user who generates the content is called the content generator.

C. Security Model

As edge nodes are deployed by third parties and can be openly accessed, different edge nodes may have different level of security. In the system model, we have three types of edge nodes in the network, which are honest edge nodes, malicious edge nodes, and speculative edge nodes, respectively. The honest edge nodes are the ones that can provide the secure caching service for mobile users. The malicious edge nodes are the nodes that may conduct attacks to destroy the network. The speculative edge node is dynamical one and determines its actions at random to provide a secure caching service or carry out a malicious attack at different moment. The ratios of honest edge nodes, malicious edge nodes, and speculative edge nodes are denoted as hr, mr, and sr, respectively. In addition, there are some selfish edge nodes among the honest edge nodes, where selfish edge nodes refuse to provide caching services for mobile users.

IV. Analysis of the Proposed Scheme

In this section, we introduce the framework of the proposed scheme, which consists of the optimal edge node selection and the trust evaluation.

A. Optimal Candidate Selection

When a mobile user (refer to mobile user j) generates a content, this mobile user can upload this content to a nearby edge node and share it with his/her friends. Here, not all edge nodes can be the candidates to cache content for mobile user j. For the smooth playback of the content, the bandwidth of the selected edge node should be no lower than the bitrate of the generated content. In addition, to ensure that some of friends can access an edge node and watch the content concurrently, the edge node should not be overloaded. Then, the total number of concurrent users to be allowed to access the edge node i can be calculated by

$$RC_i = n_i - AC_i. \tag{5}$$

Let $h_{i,j} = 1$ denote the situation that edge node i satisfies the above two conditions for mobile user j. Otherwise, $h_{i,j} = 0$. Thus, we have

$$h_{i,j} = \begin{cases} 1, & \text{if } b_i \geq bt_j \text{ and } G_j \leq RC_i \\ 0, & \text{else} \end{cases} \tag{6}$$

where G_j is the expected minimum number of current friends that can obtain the video from edge node i, which is set by content generator j. It can be calculated by

$$G_j = \lfloor \xi_j N_j \rfloor, \quad 0 < \xi_j \leq 1 \tag{7}$$

where $\lfloor \cdot \rfloor$ is the floor function and ξ_j is a percentage to show the minimum number of friends who can obtain the content simultaneously. N_j is the number of mobile users who have social relationship with mobile user j.

Then, we analyze how mobile user j selects an optimal candidate of edge node to cache contents and pays for the services. We use the reverse auction game to model the interaction between the proper candidate edge nodes and mobile user. Each candidate first sends a bid to the mobile user. Then, the mobile user will select an optimal candidate of edge node as the winner of the game according to the submitted bids.

Before the edge nodes submit bids, mobile user j should broadcast the minimum demand of caching size to all candidates of edge nodes. The caching size is the buffer size provided by the edge node to cache content segments. Let $\underline{s_j}$ be the minimum caching size required by mobile user j. It is noticed that the caching size provided by any edge node equals to the data size of several segments of content. The minimum caching size is in proportion to the number of friends and the whole data size of the content. It can be obtained by

$$\underline{s_j} = \left\lfloor \frac{\log_2(1 + \frac{N_j}{\max\limits_{j' \in \mathcal{J}}(N_{j'})})\eta_j D_j}{bt_j} \right\rfloor \times bt_j \tag{8}$$

where η_j is the adjustment parameter of minimum caching size determined by mobile user j.

After mobile user j broadcasts the minimum demand to the candidates of edge nodes, each candidate will submit the optimal bid to the mobile user, who aims to maximize its utility. Then, the mobile user selects an edge node to be the optimal candidate, with whom the mobile user can obtain the maximum utility. The utility of mobile user j with the bid of edge node i can be defined as

$$u_{i,j} = \Phi(s_i) - p_i \tag{9}$$

where p_i is the price charged by the edge node i. $\Phi(s_i)$ is the satisfaction function of mobile user j with the bid of the edge node i as follows:

$$\Phi(s_i) = \gamma \log \left(1 + \frac{s_i}{\underline{s_j}}\right). \tag{10}$$

Here, γ is the satisfaction parameter.

The utility of an edge node i can be defined as

$$\pi_i = x_i(p_i - C_i(s_i)) \tag{11}$$

where x_i is a binary variable. Here, we have $x_i = 1$ if edge node i wins game. Otherwise, we have $x_i = 0$. $C_i(s_i)$ is the cost function of edge node i, which can be calculated by

$$C_i(s_i) = \varepsilon_i s_i \tag{12}$$

where ε_i is the cost parameter of edge node i. Indeed, the detailed cost of an edge node is usually private and cannot be known by other edge nodes. But each edge node can estimate the cost by a probability distribution. Here, we assume that the cost parameter follows a uniform distribution with $[\underline{\varepsilon}, \overline{\varepsilon}]$.

After receiving the bids from all candidates of edge nodes, mobile user j will select the optimal candidate, with which the utility of mobile user j can be the largest. Different edge node has a different probability to win the game. Let P_i denote that edge node i wins the game. Therefore, the expected utility of edge node i can be obtained by

$$E\{\pi_i\} = 0 \cdot (1 - P_i) + (p_i - \varepsilon_i s_i) \cdot P_i. \tag{13}$$

Each edge node has two targets. The first is to win the game to get the opportunity to obtain the utility. The second target is to maximize the utility as the next step. Based on these two targets, the determination of the bid should consider the price, the caching size by the edge node. Thus, an optimization problem for edge node i is described as

$$\max_{(p_i, s_i)} \; E\{\pi_i\}$$
$$\text{s.t.} \; \begin{cases} \underline{s_j} \le s_i \le S_i \\ \pi_i \ge 0 \end{cases}. \tag{14}$$

To solve the above problem, we first calculate the optimal caching size for mobile user j. Then, the optimal price to charge mobile user j for providing service is analyzed.

Theorem 1: The optimal bid strategy on the caching size can be obtained by

$$s_i{}^* = \arg\max_{s_i} \quad \gamma \log\left(1 + \frac{s_i}{\underline{s_j}}\right) - \varepsilon_i s_i. \tag{15}$$

Proof: We assume that the bid $s_i{}^*$ is not the optimal strategy of edge node i. There must exist another optimal bid $(p_i{}', \; s_i{}')$, which maximizes the utility of the edge node i. Here, $s_i{}' \ne s_i{}^*$. Let

$$p_i^* = \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) - \left[\gamma \log\left(1 + \frac{s_i{}'}{\underline{s_j}}\right) - p_i{}'\right]. \tag{16}$$

Therefore, we have

$$\begin{aligned} & p_i' - \varepsilon_i s_i{}' \\ &= p_i{}^* - \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) + \gamma \log\left(1 + \frac{s_i{}'}{\underline{s_j}}\right) \\ &\quad - \varepsilon_i s_i{}' \\ &\le p_i{}^* - \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) + \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) \\ &\quad - \varepsilon_i s_i{}^* \\ &= p_i{}^* - \varepsilon_i s_i{}^*. \end{aligned} \tag{17}$$

Apparently, formula (17) is contradictory to the initial assumption of the proof. Therefore, the bid $s_i{}^*$ is the optimal strategy on caching size. ■

According to formula (15), the optimal strategy of candidates of edge node i for the caching size is as follows:

$$s_i{}^* = \frac{\gamma}{\varepsilon_i} - \underline{s_j}. \tag{18}$$

Then, we analyze the optimal price in bid to win the game and optimize the utility of edge node i. Since the optimal strategy for the nonprice attribute including the caching size is obtained by edge node i, the reverse auction game can be seen as a typical auction game, where the goods are the utility of mobile user j. With the cost of edge node i, the maximum utility of mobile user j that can be provided by edge node i becomes

$$\varphi_{i,j} = \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) - \varepsilon_i s_i{}^*. \tag{19}$$

When the optimal caching size is offered by edge node i, the utility of mobile user j with the bid of the edge node i can be obtained by

$$\hat{u}_{i,j} = \gamma \log\left(1 + \frac{s_i{}^*}{\underline{s_j}}\right) - p_i. \tag{20}$$

Combined with formula (19) and formula (20), the expected utility of edge node i can be rewritten as

$$E\{\pi_i\} = (\varphi_{i,j} - \hat{u}_{i,j}) P_i. \tag{21}$$

It is noticed that the target of mobile user j is to select an edge node, with the bid of which mobile user j can obtain the maximum utility. Then, we can have

$$u_{i,j}^* = \max\{\hat{u}_{i,j} | i = 1, 2, \ldots, I\}. \tag{22}$$

Therefore, each candidate of edge node tries to select an optimal bid price in order to maximize the utility of mobile user denoted by formula (20). Different from the traditional auction game, we analyze the reverse auction by considering that each edge node has an estimated value about the maximum utility of the mobile user defined in formula (19). And it can offer a bid defined in formula (20) to the mobile user.

For edge node i, the bid strategy to win the auction by competing with other edge nodes is given by $\hat{u}_{i,j} = \Psi_i(\varphi_{i,j})$. Since each edge node is rational, $\hat{u}_{i,j}$ increases with $\varphi_{i,j}$. According to formula (22), edge node i can obtain the payoff only when its bid is the highest among all candidates of edge nodes. Otherwise, the payoff of edge node i is zero. Thus, the probability P_i also means that the bid of edge node i is the highest among those of all proper candidate edge nodes. It can be obtained by

$$P_i = \prod_{i'=1, i' \ne i}^{I} \Pr\{\hat{u}_{i,j} \ge \hat{u}_{i',j}\}. \tag{23}$$

As mentioned above, the bid of a candidate edge node is based on the value of the maximum utility of mobile user. Thus, we can have

$$\Pr\{\hat{u}_{i,j} \ge \hat{u}_{i',j}\} = \Pr\{\varphi_{i,j} \ge \varphi_{i',j}\}. \tag{24}$$

Since an edge node cannot have the entire information about the bids of other candidates, $\varphi_{i',j}$ can be seen as a random variable for edge node i. Indeed, the reason why an edge node can not know the bids of others is that the cost parameter for an edge node is privately owned by itself. Therefore, the probability distribution function of the bids of edge node i' is

$$\begin{aligned} F(\varphi_{i,j}) &= \Pr\{\varphi_{i',j} \le \varphi_{i,j}\}\} \\ &= \Pr\{\varepsilon_{i'} \ge \varepsilon_i\} \\ &= 1 - \Omega(\varepsilon_i) \end{aligned} \tag{25}$$

where $\Omega(\cdot)$ is the probability distribution function of the cost parameter $\varepsilon_{i'}$ of edge node i'. Therefore, the probability P_i can be calculated by

$$P_i = F(\varphi_{i,j})^{I-1} = (1 - \Omega(\varepsilon_i))^{I-1}. \tag{26}$$

In order to reflect the relation between the probability P_i and $\varphi_{i,j}$, we set $P_i = H(\varphi_{i,j})$. Then, the utility of edge node i can be rewritten as

$$E\{\pi_i\} = (\varphi_{i,j} - \hat{u}_{i,j}) H(\varphi_{i,j}). \tag{27}$$

By taking the first derivative of $E\{\pi_i\}$ with respect to $\hat{u}_{i,j}$, we have

$$\frac{\partial E\{\pi_i\}}{\partial \hat{u}_{i,j}} = \frac{(\varphi_{i,j} - \hat{u}_{i,j})(\dot{H}(\Psi_i^{-1}(\hat{u}_{i,j})))}{\Psi_i'(\Psi_i^{-1}(\hat{u}_{i,j}))} - H(\Psi_i^{-1}(\hat{u}_{i,j})) \tag{28}$$

where $\dot{H}(\cdot)$ is the derivation of the $H(\varphi_{i,j})$ with the respect to $\varphi_{i,j}$. In order to obtain the maximum $E\{\pi_i\}$, let $\frac{\partial E\{\pi_i\}}{\partial \hat{u}_{i,j}} = 0$, we can obtain

$$\frac{\partial[H(\varphi_{i,j})\Psi_i(\varphi_{i,j})]}{\partial \varphi_{i,j}} = \dot{H}(\varphi_{i,j})\varphi_{i,j}. \tag{29}$$

By solving formula (29), we have

$$\begin{aligned}\Psi_i(\varphi_{i,j}) &= \frac{1}{H(\varphi_{i,j})}\int_0^{\varphi_{i,j}} \dot{H}(y)y dy \\ &= \varphi_{i,j} - \frac{1}{H(\varphi_{i,j})}\int_0^{\varphi_{i,j}} H(y)dy. \end{aligned} \tag{30}$$

Therefore, the optimal strategy for the bid price determined by edge node i can be shown as

$$p_i^* = \varepsilon_i {s_i}^* + \frac{1}{H(\varphi_{i,j})}\int_0^{\varphi_{i,j}} H(y)dy \tag{31}$$

$$H(\varphi_{i,j}) = (1 - \Omega(\varepsilon_i))^{I-1}. \tag{32}$$

Since ε_i follows the uniform distribution, we have

$$F(\rho) = \frac{\rho - \underline{\varepsilon}}{\overline{\varepsilon} - \underline{\varepsilon}}. \tag{33}$$

Then, the optimal bid price of edge node i is

$${p_i}^* = \varepsilon_i {s_i}^* + \frac{{s_i}^*}{I}(\overline{\varepsilon} - \varepsilon_i). \tag{34}$$

Therefore, there exists a Bayes Nash equilibrium of the auction if each edge node follows the optimal strategy, where the equilibrium strategies can be expressed as $\mathcal{O} = \{{o_1}^*, \ldots, {o_i}^*, \ldots, {o_{\hat{M}_j}}^*\}$ and ${o_i}^* = ({s_i}^*, {p_i}^*)$.

By comparing the utilities of mobile user j with the bids of all candidate edge nodes, the optimal candidate of edge node is chosen by

$$i^* = \arg\max_i u_{i,j}. \tag{35}$$

Algorithm 1 is provided to show the process of the optimal edge node selection.

B. Trust Evaluation

With the above auction model, the optimal candidate of edge node is selected. Next, in order to guarantee the secure caching services for mobile users, we design a mechanism based on the trust to evaluate the reliability of the candidate of edge node, to avoid the situation that the optimal candidate is malicious to conduct attacks. As the trust is based on historical experiences, mobile users need to have interactions with the edge nodes. The number of interactions matrix is denoted by

$$Q(\tau) = \begin{bmatrix} q_{1,1}(\tau) & q_{1,2}(\tau) & \cdots & q_{1,J}(\tau) \\ q_{2,1}(\tau) & q_{2,2}(\tau) & \cdots & q_{2,J}(\tau) \\ \vdots & \vdots & \ddots & \vdots \\ q_{I,1}(\tau) & q_{I,2}(t) & \cdots & q_{I,J}(\tau) \end{bmatrix} \quad \forall q_{i,j}(\tau) \geq 0 \tag{36}$$

where $q_{i,j}(\tau)$ is the number of interactions between edge node i and mobile user j from the initial time τ_0 to the current time τ.

The trust is based on the direct observations of each edge node on caching services. The direct trust of an edge node is related to three factors. First, the rating given by the mobile user is an important component of the direct trust. Second, the provided resource within each interaction has an effect on the importance degree of each rating. Third, the occurring time of each interaction can affect the evaluation of direct trust.

First, from τ_0 to τ, mobile user j has $q_{i,j}(\tau)$ interactions with edge node i. After each interaction, the mobile user will give a

Algorithm 1: The Secure Caching Algorithm.

```
Input: The video generator j, the video length L_j, the video bitrate bt_j.
Output: The optimal edge node i, the caching size s_i.
Initialize: O ← ∅. The minimum demands of caching size s_j (underlined) is calculated by formula (8).
for i = 1 : M̂_j do
    The optimal caching size s_i^* is calculated by formula (18).
    if s_i^* < s_j && s_j <= S_i then
        s_i^* = s_j.
    else if s_j > S_i then
        s_i^* = 0.
    else if s_i^* > S_i then
        s_i^* = S_i.
    end if
    The optimal price p_i^* is calculated by formula (34).
    O ← (s_i^*, p_i^*).
end for
The threshold ω_j is calculated by formula (42).
RT = 0
while RT < ω_j do
    if O == ∅ then
        return i^* = 0, s_i^* = 0.
    end if
    The optimal candidate edge node i^* is selected by formula (35).
    The direct trust degree RT_{i^*,j} is obtained by formula (40).
    if RT >= ω_j then
        return i^*, s_i^*.
    else
        O(i^*) = [].
    end if
end while
```

rating on the service of the edge node, which is

$$\mathrm{Rat}_{i,j}^{k} = \begin{cases} 1, & \text{if service is fully satisfactory} \\ 0, & \text{if service is fully unsatisfactory} \\ \in (0,1), & \text{otherwise} \end{cases} \tag{37}$$

where $\mathrm{Rat}_{i,j}^{k}$ is the rating of edge node i from mobile user j at the kth interaction. Since the content cached in edge node i can be shared by mobile user j with his/her friends, the rating of the edge node i at this interaction should consider both the rating from this mobile user and that from his/her friends. It can be obtained by

$$\begin{aligned} \mathrm{Rat}_{i,j}^{k} &= \sum_{j'=1}^{N_j} \frac{r_{j,j'}}{\sum_{j'=1}^{N_j} r_{j,j'} + 1} Ra_{i,j'}^{k} \\ &+ \frac{1}{\sum_{j'=1}^{N_j} r_{j,j'} + 1} Ra_{i,j}^{k} \quad \forall Ra_{i,j}^{k} \in [0,1] \end{aligned} \tag{38}$$

where $Ra_{i,j'}^{k}$ is the rating from the friend j' on the edge node i at the kth interaction between mobile user j and edge node i. Here, a mobile user with a higher social relation degree with mobile user j has a larger effect on the rating of mobile user j for edge node i.

Second, the candidates of edge node may provide different resources for caching services in different interactions. Namely, the caching sizes in different interactions between mobile user j and edge node i during time interval $[0, \tau]$ are different. Here, the rating of the service with a large caching size has a large effect on the derivation of direct trust. Let $s_{i,j}^{k}$ denote the caching size provided by edge node i for mobile user j in the kth interaction. $s_{i,j}^{k}$ is defined as the optimal bid s_i^* of edge node i in the kth interaction.

Third, after each interaction, the mobile user will give a rating on the service of this edge node. To derive the direct trust of the edge node, the previous ratings should be considered. Indeed, the latest rating can efficiently reflect the recent behavior of the edge node. Therefore, the interaction time can have the effect on the derivation of direct trust. We consider an exponential decay function by

$$\varpi_k = e^{-\vartheta(\tau - \hat{\tau}_k)} \tag{39}$$

where $\vartheta \in [0, \infty)$ and $\hat{\tau}_k$ is the kth interaction time.

Therefore, by considering the rating, the resource of service and interaction time, the trust degree of edge node i given by mobile user i can be obtained by

$$\begin{aligned} &RT_{i,j}(\tau) \\ &= \begin{cases} \sum_{k=1}^{q_{i,j}(\tau)} (W_k \mathrm{Rat}_{i,j}^{k} \cdot \varpi_k), & \text{if } q_{i,j}(\tau) > 0 \\ 0.5, \quad \text{else} \end{cases} \end{aligned} \tag{40}$$

$$W_k = \gamma \frac{s_{i,j}^{k}}{\sum_{k=1}^{q_{i,j}(\tau)} s_{i,j}^{k}}. \tag{41}$$

After obtaining the trust degree of the edge node, the mobile user should judge whether the edge node is trustworthy or not. A threshold value ω_j is used for mobile user j to make decision to request caching services from edge node i at time τ. If $RT_{i,j}(\tau) \geq \omega_j$, the edge node i is trustworthy to cache content. Otherwise, the edge node i is not secure, and then the mobile user should select another optimal candidate edge node. A mobile user with more friends has a higher demand of security and the content with a larger data size should be cached in the securer edge node. Then, the threshold should be dynamical and can be obtained by

$$\begin{aligned} \omega_j = \frac{RT_{i,j}(\tau)^{\max}}{\nu_j} &+ a \log\left(1 + \frac{D_j}{\max(D_j)}\right) \\ &+ b \log\left(1 + \frac{N_j}{\max(N_j)}\right) \end{aligned} \tag{42}$$

where ν_j is the adjustment parameter. $RT_{i,j}(\tau)^{\max}$ is the maximum trust degree of mobile users j on an edge node i during $[0, \tau]$. Here, a and b are the weighted parameters.

The mobile user who caches the content on a nearby edge node will share the content to his/her friends with the charge of $\sigma(\tau)$. The friends with a high social relation can obtain the content by a low price as follows:

$$\sigma_{j,j'}(\tau) = (1 - r_{j,j'}(\tau)) \cdot \sigma_j(\tau). \tag{43}$$

In addition, the share of content can also increase the social relation degree of two mobile users. When a content is shared, the social relation degree between mobile user j and j' can be updated by

$$r_{j,j'} = [r_{j,j'}(\tau) + \Delta_{j,j'}(1 + s_i{}^*)]^{+} \tag{44}$$

$$[\cdot]^{+} = \min\{1, r_{j,j'}(\tau) + \Delta_{j,j'}(1 + s_i{}^*)\} \tag{45}$$

where $\Delta_{j,j'}$ is the increment to update social relation degree. Therefore, if a mobile user wants to obtain the contents from others with low payments, he/she should also share the contents to others to increase the social relation degree.

V. Performance Evaluation

In this section, we carry out extensive simulation experiments to evaluate performance of the proposed scheme. The simulation setup is first introduced, followed by the numerical results and analysis.

A. Simulation Setup

In the simulation scenario, there is a $500 \times 500\ \mathrm{m}^2$ terrain with 30 edge nodes and 100 mobile users [28]. Initially, the ratio of malicious edge nodes, speculative edge nodes, and honest edge nodes is 0.1, 0.3, and 0.6, respectively. Among the honest edge nodes, the percentage of selfish nodes is 30%. The maximum bandwidth for each mobile user in an edge node is uniformly distributed in [0.2, 2.5] Mb/s. The allowable maximum number of mobile users to access an edge node is uniformly distributed from 30% to 60% of the number of mobile users. The caching capacity of each edge node follows the uniform distribution within [50, 100] Mb.

Initially, the social relation degrees among mobile users are randomly set within [0, 1]. The probability of generating a video

TABLE I
PARAMETERS

Parameter	Value
ϱ	1000
κ	1000
α	0.5
R_i	500
ξ_j	0.3
η_j	[0.2, 0.3]
β_j	[0.2, 0.3]
γ	0.5
ϑ	0.0001
BW	2.5 Mb/s

by each mobile user is 0.1. The initial direct trust degree between a mobile user and an edge node is 0.5. The videos are generated every $10s$ by a randomly determined mobile user. The set of bite rate generated by video is selected at random from $\{0.2, 0.4, 1.7, 1.3, 2.3\}$[29]. The minimum length of a video is $10s$ and the maximum length is $50s$. The local buffer in the mobile device is 10 Mb [29]. The quality of service provided by the honest node can be marked by a value randomly in [0.7, 1] and the quality of service provided by the malicious edge node is randomly in [0, 0.3]. The rating from each mobile user on an edge node equals to the quality of service. Other parameters have been concluded in Table I.

The following metrics are used to evaluate the performance.

1) *Secure caching ratio:* The proportion of contents that can be cached on the honest edge node to the total of contents. The secure caching ratio is defined as follows:

$$\mathrm{scr} = \frac{\bar{m}}{\bar{M}} \times 100\%. \tag{46}$$

Here, $\bar{M}$ is the total number of contents generated by mobile users within a period time. $\bar{m}$ is the number of cached contents in the secure edge node, where these replicas can be provided to mobile users to obtain a cache hit.

2) *Average saved time:* The average of the reduced delay to obtain the content cached by edge node, compared to the remote cloud server.

B. Numerical Results

The proposed scheme is compared with two conventional schemes as follows.

Random scheme (RS): In this scheme, mobile users randomly select a surrounding edge node to cache content, and the edge node randomly allocates caching size.

Auction based scheme without trust evaluation (AWT) [28]: In this scheme, the edge node is selected based on the reverse auction game. But, there is no trust evaluation mechanism to consider the security of the selected edge node.

Fig. 2 shows the comparison of the proposal with two conventional caching schemes about the secure caching ratio when the simulation time changes. In the simulation, we set simulation time to be changed from 2000 to 6000 and the proportion of malicious edge nodes, speculative edge nodes, and honest edge nodes are 0.1, 0.3, and 0.6, respectively. From Fig. 2, we can know that the proposed scheme outperforms other schemes by obtaining a better secure caching ratio at each simulation time. In the RS, the selected optimal edge nodes may be malicious edge nodes, or selfish edge nodes, which will not securely cache content, or not store the content. In the AWT scheme, due to the lack of reputation evaluation, the winner of the auction can be malicious edge node or speculative edge node, which will conduct attacks to mobile users. For the proposed scheme, the selfish nodes are encouraged to take part in the cooperation of caching contents. Especially, with the trust evaluation, the contents that need to be cached can be stored in the secure edge node with a high trust degree.

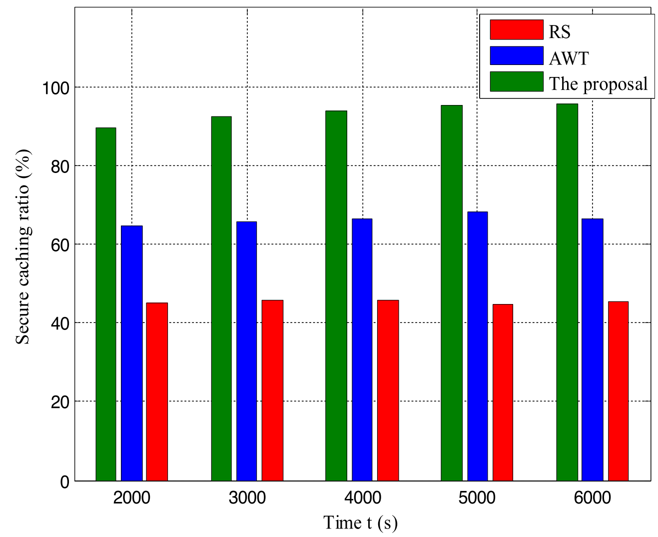

Fig. 2. Secure caching ratio.

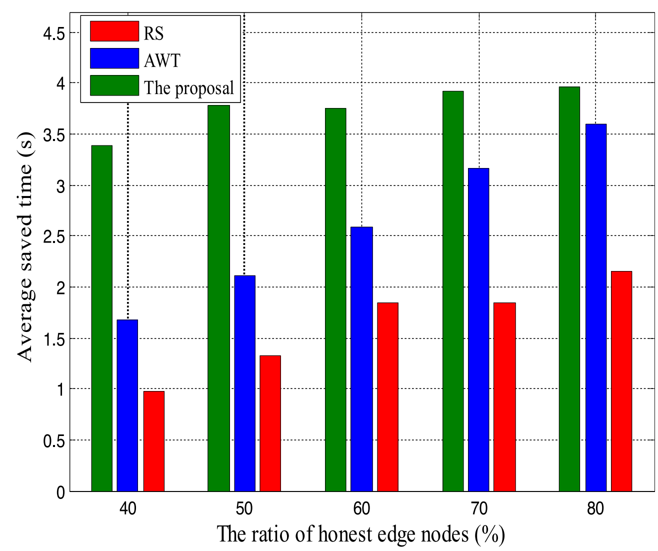

Fig. 3. Average of saved time.

Fig. 3 shows the average saved time by the comparison between the proposed scheme with other two conventional schemes, where the ratio of the honest edge nodes changes from 0.4 to 0.8. Here, the ratio of speculative edge nodes is 0. We can observe that the proposed scheme can reduce the delay more efficiently than other schemes. In addition, the change of the average saved time in the proposal is lower than those in other existing schemes. In the proposal, the caching size for each content is selected by the optimal bid. It is determined by the reverse auction game, where the mobile users can have the maximum utilities. In addition, although the ratio of the honest edge node changes, the malicious edge nodes are always recognized by the trust evaluation process in the proposal where most of contents can be cached on honest edge nodes.

VI. Conclusion

This paper has presented a theoretical game model to securely deliver content with edge nodes to save energy for green cities. In the proposal, mobile users generate and share contents with each other by caching contents in edge nodes. To encourage edge nodes to cooperatively cache contents, the reverse auction game model has been developed. Based on the strategy of each edge node, the optimal candidate of edge node for caching content can be selected. Next, in order to guarantee the security of content delivery, a trust management method is designed to evaluate the reliability of the selected candidate of edge node, by the direct trust evaluation. In addition, extensive simulations have shown that the proposal can save the energy to deliver content with a higher secure caching ratio and a lower delay than conventional methods. The future work is to discuss the privacy disclosure of mobile users when their contents are cached on the edge nodes.

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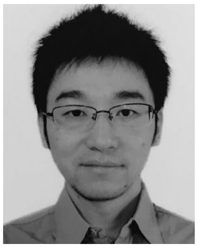

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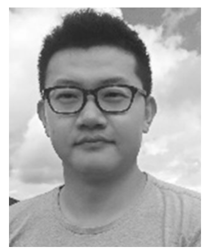

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