On the Incentive Mechanisms for Commercial Edge Caching in 5G Wireless Networks

Tingting Liu, Jun Li, Feng Shu, Haibing Guan, Shihao Yan, and Dushantha Nalin K. Jayakody

Abstract

Mobile data traffic has dramatically increased by a factor of around 100 over the last five years, while it is still expected to grow exponentially in the near future. Evidence indicates that the repetitive downloading of popular contents accounts for the increase in wireless traffic. This has consequently led to the development of edge caching technology for efficiently mitigating redundant transmissions from backbone networks by pre-caching frequently requested data at radio access networks. Among a variety of research topics in this field, the commercialization of edge caching has attracted augmented attention. In this article, we focus on the design of incentive mechanisms for commercial edge caching in 5G cellular networks, where the edge device providers (EDPs) and content providers (CPs) are the two counter-parties competing to maximize their own welfare. We first propose the architecture of a commercial caching system and analyze the revenue of the entities involved. Due to selfishness, each entity tries to achieve its highest benefit by squeezing profits from others, causing contentions of interest. Game theoretic approaches are then introduced to balance the conflicts. Four incentive frameworks are developed based on different categories of games in the context of the caching system. Afterward, we conduct case studies for three application scenarios to demonstrate the superiority of our proposed game models. Numerical results are also provided to validate the effectiveness of our proposed game frameworks.

Introduction

The ever increasing demand for entertainment and social connections at any time and anywhere brings new challenges to the current wireless communication systems. The driving forces behind this exponential traffic growth have fundamentally shifted from the steady increase in demand for connection-centric communications, such as phone calls and text messages, to the explosion of content-centric communications, such as mobile video streaming and content sharing. Cisco's prediction indicates that by 2021, wireless video data will occupy 78 percent of the total amount of wireless traffic. Unfortunately, the existing cellular system cannot keep pace with the traffic growth [1].

With the recent standardization of fourth generation (4G) communication technologies inside Long Term Evolution-Advanced (LTE-A), researchers and operators are now beginning to conceive of 5G to enhance network capacity. Disruptive innovations in 5G include the deployment of ultra-dense heterogeneous base stations and the exploitation of extra frequency bands [2]. However, besides some scenarios that have to introduce extra spectrum or increase spectrum reuse, most technologies still rely on changing the hardware equipment or network protocols. Usually, these improvements may induce extra costs and complexity to current communication systems. As such, efficient and economical approaches are highly demanded for coping with the data avalanche.

When looking into the pattern of traffic over mobile networks, a majority of transmissions are found to be repetitive, caused by frequent requests on the same contents (e.g., online videos). Also, with the prevalence of mobile cloud computing in cellular networks, these requests are directed to the centralized cloud servers located at backbone networks, where popular contents are aggregated, leading to large-scale peak time congestion. To address these issues, wireless edge caching becomes a new paradigm for future 5G that can mitigate redundant transmissions from backbone networks by caching hot data at radio access networks [3–5]. Generally, edge caching in 5G networks contains two stages: a data placement stage and a data delivery stage [6]. Specifically, in the data placement stage, popular contents are pre-stored at the edge devices during off-peak time. In the data delivery stage, mobile users (MUs) request files directly from the adjacent edge devices without triggering transmissions via backhaul channels. The definition of edge devices in this article is shown as follows.

Definition 1. *Edge devices: devices, including macrocell base stations (MBSs), small cell base stations (SBSs), femtocell access points (FAPs), and other user devices, capable of providing edge computing services to nearby end users can be regarded as edge devices. Services provided by edge devices are qualified by high data rate and low latency.*

In this article, our research focus is on the commercial edge caching systems consisting of content providers (CPs), edge device providers

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(EDPs), and mobile users (MUs). The CPs (e.g., YouTube) purchase copyrights from video producers and publish the videos on their web sites, while the EDPs can be the operators (e.g., Vodafone) who are in charge of edge devices, such as MBSs and SBSs, or can be private owners of the FAPs or user terminals. From the perspective of CPs, edge caching technology enables CPs' purchased videos to be cached in the edge devices close to their subscribers, potentially improving subscribers' quality of experience (QoE) and further strengthening their loyalties to CPs. From the perspective of an EDP (e.g., the operator of cellular network), edge caching can help offload data traffic from its backhaul channels and alleviate congestion in its core network.

By viewing the edge devices as a kind of resource, a commercial caching system needs to deal with the resource pricing and allocation issues. On one hand, the CPs are willing to rent part of the edge devices from the EDP for temporarily caching their contents in the vicinity of the subscribers. On the other hand, the EDPs make a profit by leasing the device resources. The two counter-parties (i.e., EDPs and CPs) are selfish and try to achieve the highest possible benefit by competing with each other, although both of them are the beneficiaries of the caching system. As such, it is necessary to develop essential incentive mechanisms to leverage the payoff and expenses, and to encourage the active participation of different parties. It is well known that game theoretic approaches are capable of balancing these kinds of interest conflicts by achieving the Nash equilibrium (NE), in which each entity participating in the game will be happy to maintain the status quo.

In this article, we study incentive mechanisms based on game theoretic approaches to motivate different parties participating in wireless edge caching. First, we analyze the architectures of the wireless edge-caching-enabled 5G networks. We highlight the characteristics and revenue of the entities involved in the system, and the potential interest conflicts among them. Then we develop four incentive frameworks applicable for balancing the interest competitions and achieving the NE point. These frameworks are based on four well-known game models: Stackelberg game, matching game, auction game, and contract theory. Next, we conduct case studies for several application scenarios to demonstrate the superiority of our proposed game models. Finally, future challenges and possible work are also summarized.

Architectures of Commercial Edge Caching

In this section, we present a commercial edge caching architecture in 5G networks. Multiple parties with different interests coexist in this architecture. As shown in Fig. 1, the proposed edge-caching-enabled system consists of three parties: CPs, EDPs, and a (potential) third party.

Content Providers

In general, there are multiple CPs in a caching system. Competitions for profits push them to find efficient solutions that are capable of providing their subscribers with better services. Once edge caching is commercialized, these CPs will express great interest in participating in the market since such a system can bring their products (e.g., videos and movies) close to their subscribers with improved QoE.

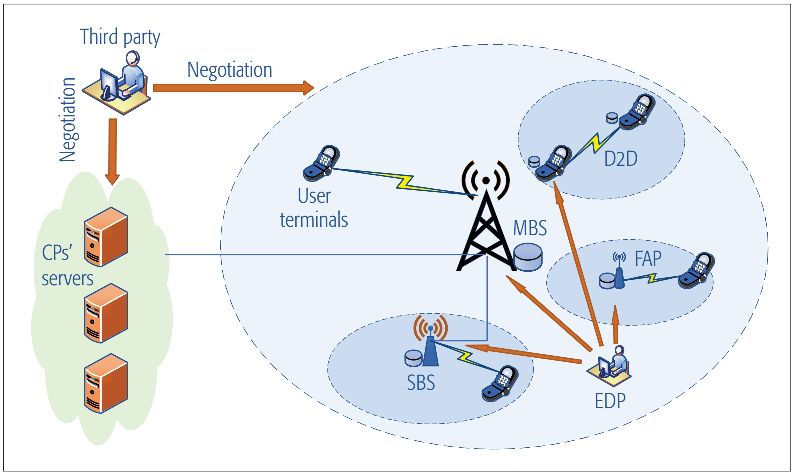

FIGURE 1. Architecture of edge-caching-enabled 5G networks.

The CPs can be classified into different types according to their provided services. Some of the CPs (e.g., iTunes U) provide online learning courses for students or self-learners. This kind of CP possesses a large number of files that cover all the majors, while the update of these contents is not frequent. Their subscribers are not sensitive to transmission latency. Some CPs offer live sports to their subscribers. Although the requests mainly focus on a few files at the same time, users may demand real-time and low-latency processing. Some other CPs (e.g., YouTube) supply entertainment videos to their customers. The update rate of contents is normally high, and users' preferences reveal obvious geographical or social characteristics.

Edge Devices and Edge Device Providers

The EDPs are the edge facility owners. Taking the network service operator as an example, it owns the MBSs and SBSs. MBSs have sufficient large storage, and thus can cache a large number of files or even the entire file library. Moreover, the deployment of MBSs is well designed for covering a large portion of the local area. In contrast, the storage of an SBS is relatively limited, and the locations of SBSs are more random compared to those of MBSs. However, SBSs are cheaper and more efficient to deploy, and more convenient for MUs to access.

Besides the above mentioned operator-owned facilities, there are some detached network facilities, such as FAPs. In general, FAPs are likely to be privately owned by certain service providers or home users. Usually, FAPs have medium capacity as well as fixed positions. Thus, they can pre-cache part of the popular files and provide local coverage. However, since FAPs are usually located closer to MUs compared to MBSs and SBSs, they can provide better services (e.g., higher transmission rate and lower transmission latency) to MUs within their coverage.

At the same time, user devices, as a kind of edge devices, are widely spread and may freely move in the network. As such, a user device can be utilized to cache files and, upon request, transmit them to other mobile devices in the

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same community via device-to-device (D2D) communications. However, user devices have very limited capacity and constrained power. Privacy concern is also an important factor that affects their involvement in caching activities.

From the above discussions, it can be seen that a variety of edge devices form a multi-layer heterogeneous caching system, with each layer having a specific characteristic. How to stimulate EDPs to participate in commercial activities and how to create reasonable resource allocation and pricing are the two essential challenges.

The Third Party

Since CPs have distinct requirements, while EDPs possess different forms of resources, it is potentially efficient to introduce a third party to balance the supply and demand. The third party, usually acting as an agent or a broker, harvests the caching resources and resells them to the CPs. In some cases, an EDP itself acts as the agent. In other cases, a conflict-free third party is established to act as the agent.

In this scenario, edge devices need to periodically report their remaining storage sizes, locations, available periods, and prices. Then the third party harvests the caching resources and marks them with different properties and prices. Finally, each CP obtains its desired type/fraction of resources through consulting the third party. The third party may gain profits by first purchasing resources from EDPs and then reselling them to CPs.

Incentive Mechanisms Based on Typical Games

When we model the commercial edge caching system as a trading market with different types of traders and resources, we need to study the interactions among these rational participants. It is well known that game theory is an effective method, with a set of mathematical tools to solve resource allocation and interest balancing [7]. In this section, we study some typical game models applicable to edge caching for resource pricing and allocation.

Stackelberg Game

We propose a Stackelberg game model to solve the resource allocation in an information symmetric environment, where the side information of both parties are assumed to be known to each other. In a Stackelberg game, there is a hierarchy, where a leader who moves first declares its strategy, and a follower then chooses its best response accordingly [7].

In our commercial edge caching system, there are multiple hierarchical relationships when considering different kinds of trading resources. For example, we can consider the EDPs as the leaders and the CPs as the followers, while the network facilities possessed by the EDPs are considered as a specific type of resources [8]. The EDPs first set the prices of their resources, say, the SBSs, and then each CP determines which EDP it should follow and how much of the resources it should purchase regarding the given prices.

The EDPs (e.g., network operators) have a strong intention to offload traffic from the backhaul channels by first renting popular files and then caching them to the edge devices. The contents owned by the CPs can also be treated as a kind of trading resource. We model the CPs as leaders and the EDPs as followers. Each CP leases the copyrights of the contents and marks them with different prices first. Then the EDPs determine how many contents they need to rent subsequently. Similarly, the resource allocation and pricing can be solved under the Stackelberg game framework as well.

Similar applications can easily be extended to the scenario consisting of the third party and CPs. The third party harvests caching resources from EDPs and marks the collected resources with different prices. Then it resells the resources to CPs to make a profit. The hierarchical relationship between the third party and CPs also depends on the types of trading resources.

Matching Game

The applications of a matching game can be classified into different types: bipartite matching problems with two-sided preferences, bipartite matching problems with one-sided preferences, and non-bipartite matching problems with preferences [9, 10].

One possible application of a matching game in the caching system can be designed as follows. The involved parties are divided into two disjoint sets, corresponding to the two participants (i.e., the CPs and the EDPs). For example, as stated earlier, MUs' preferences reveal obvious geographical or social characteristics, and they all want to have their favorite files placed in nearby network devices [11]. Therefore, in order to satisfy their subscribers, CPs have different preferences toward various edge devices. Also, an EDP might prefer different CPs, with its aim to offload more data traffic from the backhaul channels or to gain more profit. Considering the third party scenario, after harvesting, ivarious edge devices have different properties, such as locations, densities, or transmission powers. Then the third party matches these devices with different CPs, with the aim to gain more profit. This kind of problem can be modeled as a two-layer matching problem. We first match files to specific edge devices, and then match each CP to the optimal EDP. It is worth mentioning that proof of the stability is essential for matching games.

Auction Game

Auction theory is widely used in the information asymmetric environment where there are usually not enough resources for all the buyers, and the buyers' valuations for the resources are not known. In general, there are three parties involved in an auction game: the buyer to be the bidder, the resource holder to be the seller, and a third party who conducts the auction processes to be the auctioneer. The final prices are determined by multiple rounds of bidding through competitions among the potential buyers [12].

In the proposed wireless caching networks, one side usually has certain private information that cannot be observed by the other side; thus, it is reasonable to model the network as an information asymmetric environment. In this scenario, when the network facilities are treated as resources, the possessor of the edge devices (i.e., the EDP) can act as the seller, the CPs act as the buyers, and the conflict-free third party acts as the auctioneer. Alternatively, when the contents are regarded as resources, the CPs act as the sellers, while the EDP plays the role of a buyer. Many auction types can be modeled in this scenario, such as demand auction, supply auction, and double auction. Among these various auction models, the key problem that should be properly addressed is the rule design, based on which the auctioneer can control the game outcome and prevent cheating.

Contract Theory

Contract design is also widely used in the information asymmetric environment. At the beginning of the contract approach, the seller/employer, as the monopolist of the market, has designed and posted the prices for its resources. Then the buyers/employees need to decide whether to join this game and which contract to sign. The applications of contract theory can be classified into different categories, such as adverse selection, which refers to the problems of hidden information, and moral hazard, which relates to the problems of hidden actions [13].

In the adverse selection problem, the seller lacks certain information about the buyers due to the information asymmetry. It then forces the buyers to reveal themselves by choosing their desired contract. Based on the revelation principle, the seller will post multiple contracts (q, p) designated for different types of buyers, where q is the quality of resources, and p is the corresponding price [14]. For the edge caching system, we can divide the network facilities into different qualities (e.g., different transmit power levels, different storage capacities, or different coverage). Meanwhile, CPs can be featured by multiple types based on their popularity, which can be quantified by the number of subscribers, among the MUs. The EDP, as a monopolist, offers the optimal contracts, which are combinations of quality and price, to maximize its profit. At the same time, each CP chooses the optimal contract entry that maximizes its own profit.

In contrast to adverse selection, the moral hazard problem arises after the contract has been signed. The employer designs the contract (a, r), where a refers to a certain action, and r is the corresponding rewards, to force the employees not to deviate from their chosen actions. In our caching system, one CP can be modeled as the employer who intends to hire some network devices to store its contents. The network devices can be regarded as the employees by exerting transmission powers or storage capacities to gain revenues. The CP designs the optimal contracts, which are combinations of action and reward, to guarantee that the network facilities do not deviate from their chosen actions.

Case Studies with Numerical Results

In this section, we conduct case studies based on some game models presented in the previous section and provide some interesting numerical results.

Matching Game

Matching games in wireless caching networks are mostly utilized in the data placement stage. The MUs' downloading latency can be effectively reduced by properly matching the edge devices to CPs. Here, we consider a caching system with CPs, FAPs, and MUs. We first allocate CPs' files to FAPs and then associate MUs with the best FAPs. This is a two-tier matching game, with a particular focus on minimizing the system transmission latency.

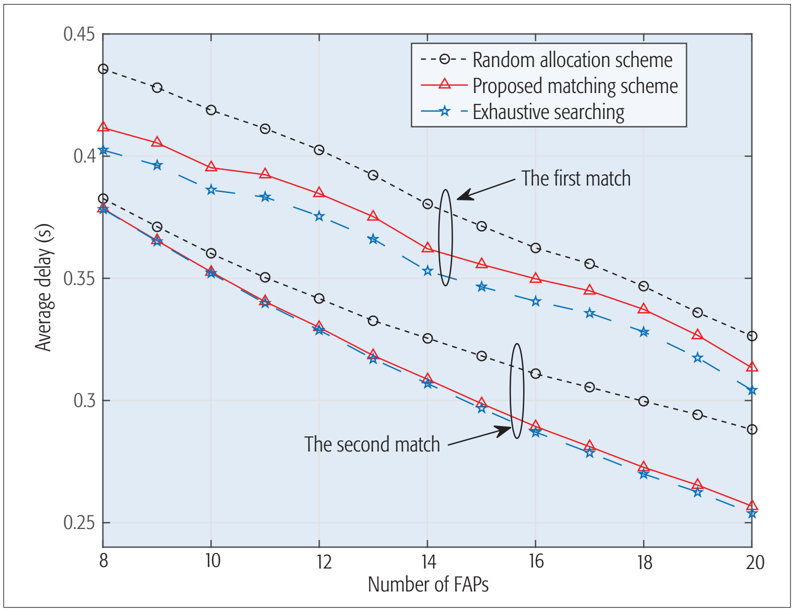

FIGURE 2. Average delay vs. the number of FAPs for the matching-game-based application.

In Fig. 2, we vary the number of FAPs from 8 to 20 to verify the performance of downloading latency after each matching. Figure 2 demonstrates the effectiveness of the proposed matching scheme in decreasing downloading latency, and it can be noticed that the latency, after the second tier matching is performed, can be further reduced. It can be seen that the proposed matching scheme performs better than the random allocation scheme, and it has a highly comparable performance with the exhaustive searching scheme.

Similar applications can be extended to the social networks. The problems in social networks mainly concern how to efficiently select important users (IUs) and how to allocate content files to IUs, considering the downloading latency and social welfare. In the social-aware scenario, users' social properties are exploited to generate the utility functions of IUs and CPs.

Auction Theory

As explained earlier, the auction-based approach is a series of operations on selling and buying a commodity whose price is undecided.

Here, we consider a network with one EDP and multiple CPs. The EDP, as the seller, sells its resources to the CP buyers. The EDP leases its SBSs to the CPs. CPs cache their files, and further reduce the downloading latency of their subscribers. Since in this scenario multiple CPs bid for a commodity being sold by the EDP, this auction can be modeled as a demand auction. We first develop the utility functions of the EDP and multiple CPs. Then we formulate an iterative auction process in order to reach the optimal price and resource allocation. Moreover, deception is considered in the proposed networks, and an ascending-bid approach is adopted to prevent cheating.

Figure 3 illustrates the profits of CPs in two situations of employing the cheating-proof scheme and without it. Figure 3 demonstrates the effectiveness of the cheating-proof auction scheme in allocating resources to CPs and preventing each CP from cheating the EDP. Moreover, each CP reaches its maximum profit when cheating factor equals 1. This indicates that each CP should not cheat on EDP; otherwise, it will not get the optimal profits.

Contract Theory

We now discuss a wireless caching network which is modeled as a two-layer transmission system, where transmissions on the first layer are via conventional backhaul channels, and transmissions on the second layer are through FAPs. As stated earlier, the FAPs are generally owned by private users, and they need a conflict-free third party to represent them in negotiating with other parties.

Different from our previous work in [14], here we consider the economical impacts between the first layer and the secondary layer. In this scenario, there are three choices for the CPs. The first choice is to transmit files via the conventional backhaul channels. which are owned by a network service provider (NSP), say, an operator. The second choice is to rent certain coverage of the FAP from the third party. The last choice is to purchase a combination of some coverage from the FAPs and some backhaul channels from the NSP. The first layer (i.e., the backhaul channels) can provide deterministic services to MUs, while it may induce repetitive transmissions on backhaul channels. The second layer (i.e., the FAPs) may offer uncertain services due to the constraints on storage capacity and coverage limitation, which may induce failure to respond to all the requests of MUs.

On one hand, the third party wants CPs to rent the coverage resource of FAPs as much as possible to maximize its own profits. Thus, the third party should evaluate the uncertainty of the offered services and determine the optimal prices, remaining competitive against the first layer. On the other hand, each CP needs to estimate their MUs' tolerance on the service uncertainty, and decide whether the uncertainty of the purchased service is worth the price.

Information asymmetry is assumed in this network. That is, the third party does not know the specific popularity of each CP, while it only knows the distribution of CPs' popularity among MUs. The third party develops the optimal contracts (i.e., a menu of coverage and prices) concerning the MUs' tolerance, as well as the reserve costs. Here, reserve costs represent the costs when files are transmitted over the conventional backhaul channels.

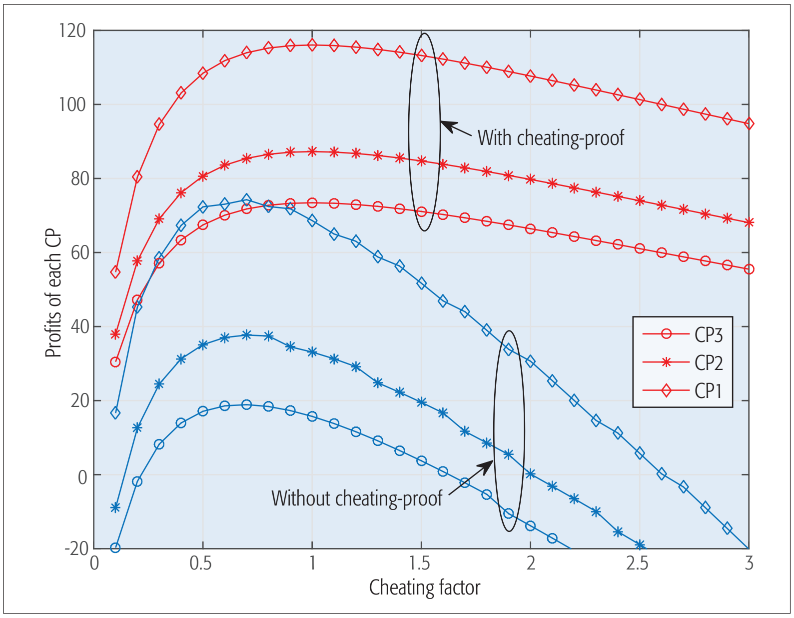

FIGURE 3. The cheating proof mechanism for an auction theory application.

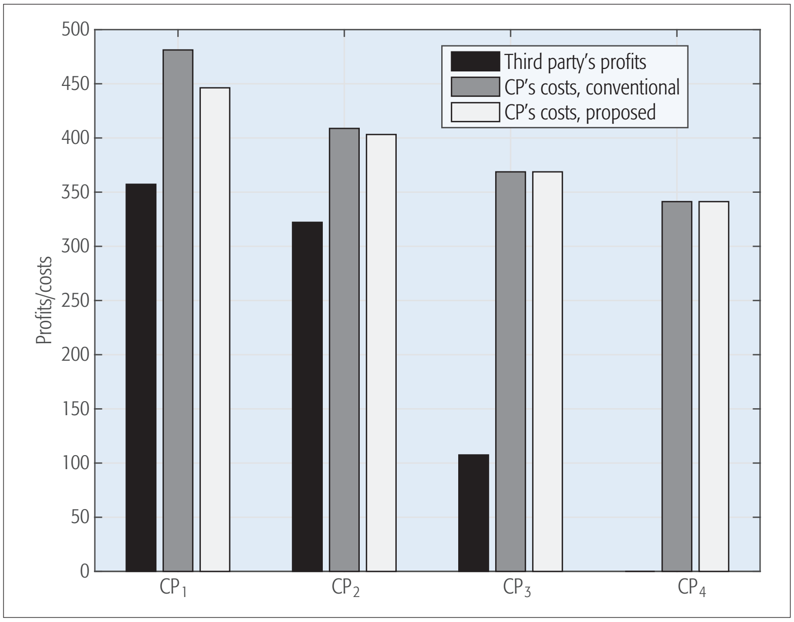

FIGURE 4. Comparisons between the proposed two-layer network and the conventional network.

Figure 4 compares the performance between the proposed two-layer networks and the conventional network (i.e., the backhaul channels). Figure 4 illustrates the third party's profits and CPs' costs on the two networks, respectively. The third party's profits come from selling FAPs' coverage on the secondary layer. It can be seen that it gains positive profits on CP_1, CP_2, and CP_3, while it gains nothing from CP_4 due to the fact that CP_4 does not purchase any coverage from the third party. Reserve costs on the conventional network where files are all transmitted via the backhaul channels can be regarded as a baseline. It can be observed that CP_1's and CP_2's costs on the proposed two-layer networks are smaller than the baseline. While CP_4 does not involve the secondary layer, its costs remain the same on the two networks. CP_3 also has the same costs on the two networks. This is due to the fact that only three CPs participate in the secondary market; in order to maximize the profits of the third party, costs of the lowest type (i.e., the costs of CP_3) are designed equal to the reserve costs.

Discussions

The four game models discussed in this article are summarized in Table 1, illustrating their features and the applicable scenarios in wireless caching. It is known that there are quite a lot

Game models	Key features	Applications in edge caching
Stackelberg game	• Non-cooperative • Hierarchy structure • Nash equilibrium	• The EDPs to be the leaders and the CP as the follower, while the network facilities charged by the EDPs are considered as resources. • The CP as a leader and the EDPs as the followers, while the contents owned by CPs are considered as resources.
Matching game	• Disjoint sets • Preference lists • Stable • Optimal solutions	• CPs have different preferences towards various network facilities. Meanwhile, the network facilities owner, i.e., the operator, prefers different CPs. A two-layer matching problem can be modeled. Firstly, we match files to specific edge devices, and then match each CP to the optimal EDP.
Auction theory	• Information asymmetry • Not enough resources • Multi-round • Time consuming	• When the network facilities are treated as resources, the resources owner, i.e., the operator, can act as the seller, the CPs act as the buyers, and the conflict free third party acts as the auctioneer. • When the contents are treated as resources, the CPs act as the sellers, while the EDP plays the role of a buyer.
Contract theory	• Information asymmetry • Efficient • Adverse selection • Moral hazard	• Adverse selection: we divide the network facilities into different qualities, for example, different transmit power levels, different storage capacities, or different coverage. Meanwhile, CPs can be featured into multiple types based on, for example, their popularity. The EDP designs the optimal contracts intended for different CPs to maximize its profits. • Moral hazard: one CP can be modeled as the employer. The network facilities can be regarded as the employees. The CP designs the optimal contracts to guarantee the network facilities do not deviate from their chosen actions.

TABLE 1. Table of the features and application scenarios of typical game models.

of differences among the four games. Contract theory, which has determined and posted the optimal prices/rewards at the beginning of the game, is more efficient compared to auction game. Stackelberg game offers both sides autonomy to maximize their own profits, while contract theory forces the buyers/employees to reveal themselves by choosing the intended contract entries to maximize the sellers'/employers' profits. Matching game is a mathematical framework describing the mutual relationships among players over time. Matching game, where players propose preference lists instead of the specific utilities, is applied in a semi-distributed manner such that some of the operations are done locally while some other operations need a centralized agent.

Besides the prominent differences, they have certain overlaps in some ways. In Stackelberg game and contract theory, the player who holds the strong position imposes its own strategy on the counter-parties. The player in the strong position is the leader in Stackelberg game, and it is modeled as the monopoly seller in contract theory. In auction game and contract theory, the incentive compatibility constraint is applied to make sure that all players truthfully reveal their types. Furthermore, auction theory can be regarded as multi-lateral adverse selection in contract theory.

Future Work

There are multiple aspects related to wireless edge caching based on game theory. In what follows, we highlight some potential research directions for further works.

Competitive Sellers: In most applications, we assume one seller (i.e., one EDP or a single third party). However, there should be multiple sellers, as stated earlier, such as multiple layers of network facilities with distinct characteristics. Some interesting works can be expected when competitions between multiple sellers are taken into consideration, especially employing the contract theory scheme.

Multi-Dimensional Incentive Models: There are multiple types of resources in edge caching networks. Not limited to only one kind of resource, one can extend models to multi-dimensional resources. For example, considering SBSs, the storage capacities and transmit powers can be regarded as two-dimensional resources. The seller can offer any of these items or special deals on bundles of them.

Hierarchical Game Model: We have addressed a two-layer matching application earlier, where each layer utilizes the same game model. Since the proposed wireless caching scenario has a typical hierarchical structure, it is promising to apply hierarchical game models between different participants [15]. For example, we first use matching game to optimally allocate CPs' files to specific edge devices, and then we use contract theory to model the interactions between CPs and EDPs.

Conclusions

In this article, we have presented the architectures of the edge-caching-enabled commercial system in 5G networks, provided some typical game models, and discussed some applications of game theory. In particular, we first analyze the interests of multiple parties and give some typical game models to illustrate their interactions. To comply with future trends in 5G networks, we have provided some applications of game theory. From these works, we have seen the effectiveness of applying game theory in the proposed edge caching systems, such as reducing downloading latency, preventing cheating, and decreasing buyers' costs. Finally, we propose some research directions, including the competitive sellers problem, multi-dimensional incentive design, and hierarchical game model. This article has provided some insights on game theory in designing incentive mechanisms for the commercialization of future edge caching systems.

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