The Business Side of Wireless Edge Caching: A Game Theoretical View

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Abstract

Future wireless systems enable content communication to be offloaded towards the network edges instead of allocating in centralized cloud. In this paper, we investigate the incentives in edge caching networks via tools from game theory by considering heterogeneous edge systems and various caching behaviors. Particularly, we analyze the competitive and cooperative interactions of multiple stakeholders involved in caching systems with the limits of caching capacity and backhaul resources. The participants in the wireless caching network are modeled as rational players due to their selfish nature. The roles of these players in various caching scenarios are thoroughly discussed from the business point of view including their strategies and utilities. The appropriate game models to study the different players are proposed with the solution concepts and algorithms. Given the existing literature, we investigate the potential research challenges concerning wireless edge caching and game models to solve them. A case study is examined showing the effectiveness of applying game theory into wireless cache-enabled networks. The numerical simulations illustrate that our proposed game models result in the win-win solution.

Index Terms

Edge caching, cache incentive, game theory, wireless networks

I. Introduction

A tremendous increase in mobile phones and connected devices is expected to lead to 800% increase in wireless data traffic by the end of 2020, while video-on-demand constituting 75% of the world's mobile traffic [1]. Many research and industrial entities are looking for innovative solutions to sustain this growing demand in the context of 5G wireless networks, with key performance challenges in throughput, end-to-end delay and energy efficiency. Despite a myriad of technological advances at the physical (PHY) and medium access control (MAC) layers such as massive multiple-input multiple-output (MIMO), mmWave and carrier aggregation, researchers are also looking for novel architectural components of the radio access network (RAN) in 5G such as cell densification, wireless backhauling and self-organization. While small cell densification is clearly one way to go, their dense deployment pushes operators to also apply high-speed backhaul links, which in some cases might be costly in practice. In this regard, content caching at the edge of network, namely at the small base stations (SBSs) and mobile terminals, aims to tackle with these limited-backhaul issues in dense 5G networks, by bringing contents (i.e., video, image and files) closer to the users, thus reducing end-to-end delay and avoiding backhaul usage [2]. In fact, wireless edge caching does not only deal with limited backhaul issues but also enables advanced PHY techniques for achieving higher throughtputs [2]. Therefore caching is seen as a key topic for upcoming 5G wireless networks.

Recent literature on wireless edge caching focuses on several technical aspects, including traffic modeling, content popularity learning under security and privacy constraints, optimal content placement, scaling laws, coded caching, joint designs with PHY techniques such as cache-enabled multicast, coordinated multipoint and interference alignment[1]. However, successful implementation of wireless edge caching is not only associated with the technical aspects but also requires a deep investigation of content-trading and business incentives. This calls for development of caching incentive mechanisms which involve interactions of multiple stakeholders: users, telecom operators, content providers, and even government entities. All these entities compete for the limited resources such as the storage/caching capacity and the caching placements. On the other hand, they may also cooperate for less caching payment or more revenue from caching. This naturally raises game theoretical models and analysis into several edge caching scenarios to address the economical aspect of caching and capture the interactions among the different entities that are involved in the caching process.

Game theory is a branch of mathematics studying and modeling the resource conflict and cooperation problems among intelligent rational players. In general, the successful applications of game theory has occurred notably in those related to information and communication technologies [3]. An increasing interest in the topic of game theory in wireless caching enabled systems is arising as evidenced in recent literature [4]–[10]. Content trading and pricing mechanisms have been a longstanding interest in networking community, aiming to design intelligent mechanisms between service providers, end-users and other types of players for content delivery and information centric networks [11].

With the rise of wireless edge caching, current growing literature extends efforts to cache-enabled wireless networks, looking for caching incentive mechanisms while considering physical

[1]For relevant discussions about wireless edge caching, we refer the reader to [2].

layer characteristics and new sets of players. For instance, a Stackelberg game between a single mobile network operator (MNO) (leader) and multiple content providers (CPs) (followers) has been formulated in [4], showing that the incentive caching mechanism among these players leads to a Nash equilibrium (NE), which is an equilibrium in caching quantities of the requested contents from all the CPs given the caching prices from the MNO. Both utilities of the leader and the followers are maximized. Another Stackelberg game model but in the context of device-to-device (D2D) networks has been studied in [5]. Other frameworks are proposed in [6] based on Stackelberg game to model the interactions between a single MNO and multiple privately-owned SBSs, as well as between the MNO and users [7], [8]. Additionally, a caching incentive model based on contract theory has been proposed in [12], where the sufficient and necessary conditions for the feasibility of a contract is given in the presence of the private information at the CPs. These works clearly show the need of incentive mechanisms for wireless edge caching, and point out a detailed investigation for successful implementation of cache-enabled 5G wireless networks modeled using tools from game theory. An overview of several game theoretical models for proactive caching can be found in [13].

Based on these observations, the main contribution of this work is to extensively investigate game-theoretical incentive mechanisms in cache-enabled 5G wireless networks. In Section II, we overview the role of pricing mechanisms in edge caching and discuss related stakeholders/players, game models and solution concepts. In Section III, we summarize the current caching models using game theory. Moreover, associated research challenges and possible solutions are elaborated. In Section IV, we present a recent case studying a Stackelberg game played between the MNO and CPs. The benefits of applying game theory into edge caching systems are supported with the numerical simulations, and discussions are carried out accordingly. Section V concludes the paper.

II. Game Theory for Wireless Edge Caching

The current research on wireless caching mainly considers the data placement issue optimized for reducing the download delay. However, the entire caching system design involves numerous issues apart from data placement [9]. Particularly, to design the efficient caching system from the economics perspective is of great importance. Multiple entities are involved in the wireless caching system, especially when we consider the proactive wireless edge caching modeled in a heterogeneous network (HetNet) with small cells. Provided the limited resources such as the

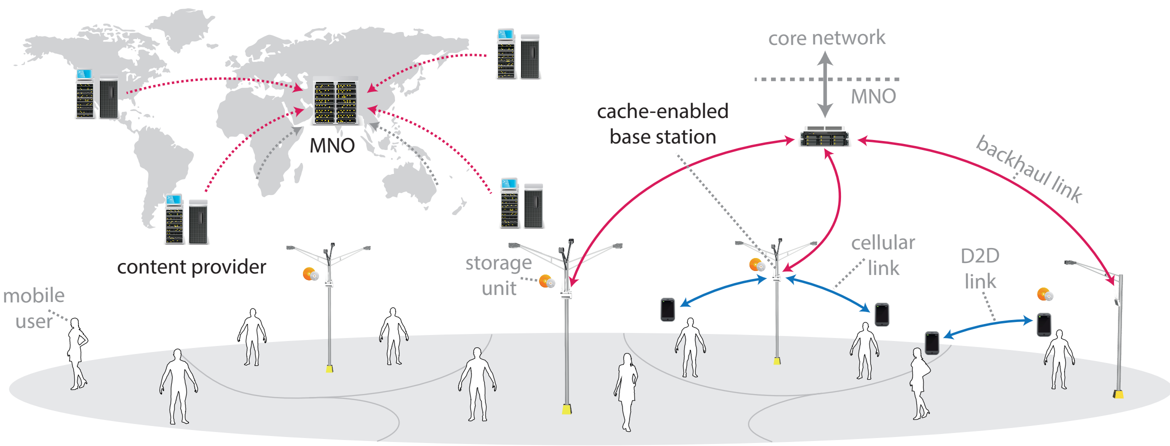


Figure 1: An example of caching scenario where multiple CPs are competing for caching their contents at the cache-enabled base stations of the MNO, therefore satisfying their users in that geographical region.

caching capacity, the transmit power, or the backhaul resource, different entities including the CPs, the MNO and the SBSs will either compete or cooperate with each other. Game theory provides us a plenty of methodologies to deal with such commercial issues consisting of conflicts and cooperations. The entities of the future cache-enabled HetNets can be considered as the rational players in a properly modeled game. Each of them is considered rational and maximizes its own utility. In this regard, a typical game in a general form $\mathcal{G} = \mathcal{G}(\mathcal{M}, \mathcal{S}, \mathcal{U})$ consists of the following components:

- The set of players in $\mathcal{G}$ is denoted as $\mathcal{M} = \{1, 2, \ldots, M\}$. The players in wireless edge caching system include CPs, MNO, SBSs, D2Ds, mobile users and the government serving as the policy maker.
- The feasible action (strategy) set of the M players is denoted as $\mathcal{S}$, where $\mathcal{S} = S_1 \times S_2 \times \cdots \times S_M$. The strategies for different players include transmit power, caching quantities, caching prices, caching placements and caching contents.
- The benefit of every player $m \in \mathcal{M}$ is given by a utility or a cost function U_m. Typical utility functions involve the revenue denoting the benefit gained from caching and the possible corresponding caching cost or the payment for caching.

In the following, we shall provide the possible players including their strategies and utilities related to the cache-enabled wireless systems, as well as the appropriate game models to solve them in detail.

A. Set of Players

In game theory and economics, the participants are commonly considered to be perfectly rational. In other words, they always perform in the way that maximizes their own utilities. In the following, the possible players involved in the caching system modeled as a game $\mathcal{G}$ are provided. Their main benefits and costs are analyzed for different game formulations, respectively.

Mobile Users. The quality-of-service (QoS) of downloading the desired contents such as videos streams and pics is the main concern of the mobile users. This QoS can be the delay of downloading a content or the data throughput. Since future wireless edge caching offers the users the possibility to download the desired contents from SBSs or other D2D users located much closer than from the base station (BS), the users benefit from caching for less power consumption, reduced delay and even lower data transmission prices. This motivates the users to participate in the caching system. However, due to the limited caching capacity and the interference coupled with each other, the users may compete with each other for the association of cache-enabled SBSs. In the case of D2D caching, the cooperation can be incited due to the compensation paid by the BS or other D2D users for helping cache and download the contents.

CPs. The CPs such as Facebook and Youtube are concerned about the satisfaction of their users. On the one hand, the CPs definitely benefit from caching because the QoS of their users is improved by proactively serving peak-hour demands during off-peak times [2] with caching. The QoS achieved by the users of each CP highly depends on the performance on the caching policy deployed by the MNO. On the other hand, due to limited storage capacity of the SBSs, CPs cannot cache all their contents. Thus, the CPs compete to maximize the amount of storage space they request. Additional prices should be charged from the CPs for the caching services. The CPs will have to optimize their utilities by balancing the potential caching benefit and the additional cost for the caching requests, given the strategies of other CPs. Meanwhile, there are constraints on the CPs such as data privacy so that they may not be willing to share the content and cache them at the SBSs. Different incentive mechanisms should be designed for various cases of the CPs with the prices as a tuning factor to consider the problem thoroughly.

MNOs. The wireless edge caching enables the MNO to reduce the pressure and cost significantly on backhaul transmission for highly demanded data streams. An MNO plays as a virtual controller of the cache-enabled SBSs and the CPs. Therefore, the MNOs may charge additional money from the CPs and as well the mobile users. The main cost is the caching storage cost, which is a function of the caching capacity of all the caching-enabled SBSs, the access probability of the caching contents, the transmission power and the backhaul cost. The MNOs play an important role to optimize the amount of caching contents and the placement of the caching policy. The MNO is responsible to design the efficient caching policy based on the paid price and the requested QoS by the CPs, or to optimize the caching prices by estimating the requests of CPs.

SBSs. The cache-enabled SBSs serve as the actual components to carry out caching. By caching the popular contents, the CPs improve the QoS of their mobile users and the corresponding MNO reduces the backhaul transmission. Therefore the SBSs may benefit from additional reward of caching. As a result, multiple SBSs located close to each other may compete for the popular caching contents and the association of mobile users in the same coverage area. Their cost consists of the caching memory cost and the transmit power consumption that are required for achieving the demanded QoS by the users.

D2D Nodes. D2D communications enable a mobile user (or machine) to communicate directly with other mobile users (or machine) in its vicinity [5]. Any D2D user who caches the desired content of a certain user can serve as the caching component and transmit the content via the D2D communication. Therefore, this technique can be adopted to enhance the caching performance by improving the spectrum utilization of the network and the access delay of the caching contents. Due to the selfish nature of the D2Ds users, they may not be willing to cache and serve other users for free because it is costly in terms of storage space and transmit power and each of the D2D users only caches its favorite contents. However, on the other hand, the MNO wants to minimize the traffic load via backhaul link. This goal is only accomplished if proper incentive mechanisms, such as compensation prices, are introduced into the network so that the efficient D2D caching is motivated. In such cases, the D2Ds users can be considered as either non-cooperative or cooperative players in the game. The hierarchical game can also be introduced to model the interaction between the MNO and the D2D users.

Government Entities. The government usually plays the role of policy makers to organize the caching entities and regularize the caching rules, such as the allocation of frequency bands, the reasonable lower or upper bounds of prices for caching in the application layer. The government should also monitor the activities of different entities and design the mechanisms in order to prevent the misbehavior such as cheating on the end-to-end channel state information (CSI), prices or caching capacity of different entities in the system.

All these entities can benefit from caching the predicted popular contents at closer locations by cooperation or competition, which yields the incentives to analyze the algorithms to implement the proactive wireless edge caching by proper game models.

B. Game Theoretic Models for Cache Incentives in Small Cell Network

This section introduces multiple game models that are suitable for different scenarios of proactive wireless caching with the aforementioned players. The potential strategies $\mathcal{S}$ of the involved players in various caching game models are investigated and their utilities $\mathcal{U}$ to maximize their own interests are analyzed.

1) Hierarchical Game: The sequential game leads to a more competitive equilibrium than the simultaneous move game.

When considering the caching incentives among different entities involved in wireless caching, the hierarchical (Stackelberg) game is suitable to model the caching problems between the MNO and the CPs, or between the MNO and the SBSs, where the MNO plays as the leader to take the caching decisions. The strategy of the leader MNO is the price charged from (paid to) the followers for caching requests (placement). Given the caching prices from the leader MNO, the followers CPs (SBSs) respond with their strategies of caching quantities, in which a non-cooperative or a cooperative (coalitional) game can be formulated as a sub-game. Several classical games can be constructed as sub-games within the setup of the Stackelberg game. Here we list the most commonly used ones as follows.

- **Cooperative (Coalitional) Game**: Cooperative game theory examines how the rational actors can benefit from voluntary cooperation. From the analysis above, the D2D users can formulate a cooperation since all of them benefit from caching and helping transmitting data streams to others. The strategy set of the D2D users in this game involves the prices for caching and forwarding the contents, the transmit power to manage the interference among each other and the association protocol based on the geographical topology. The utility of the D2D users is the benefit from caching and help forward the contents to other users. Another case exists among cooperative MNOs and SBSs or CPs, where groups and coalitions can be built up.

  On the other hand, if there exists not only selfish, but also malicious players in the wireless system, then a coalitional game can be formed among the colluded players. This malicious behavior modeled as their strategy includes cheating on the caching capacity for higher revenue (e.g., cache-enabled SBSs and D2D users), or cheating on access probability of contents for lower charge prices (e.g., CPs and mobile users). The players are assumed to choose which coalitions to form, according to their estimate of the potential benefit divided among coalition members. The characteristic function describes how much collective payoff a set of players can gain by forming a coalition. As a result, the mechanism should be designed to prevent the coalition or collusion of the malicious players in the game by introducing punishment such as higher charge prices.

- **Non-cooperative Game**: Non-cooperative game theory can be used to model the competition of the players (e.g., mobile users, CPs, MNOs and SBSs). Due to the limited caching capacity of the wireless system, the CPs (or users) compete for the caching quantities of their most popular contents. Given the compensation prices for caching, the SBSs under a single MNO or different MNOs may compete for the popular contents from the CPs. Non-cooperative game is the most appropriate mathematical tool to deal with this kind of conflict problems, where each entity involved in the corresponding caching system is considered as a rational player competing with each other. Given the caching prices per unit of caching contents, the strategy of the CPs (users) is their requested quantity of caching contents and the strategy of the SBSs (MNOs) is the detailed caching policy.

2) Auction/Bargaining: Numerous types of auction can be adopted for the analysis of caching problems. In general, an auction includes two parties of players: the bidders bidding for the quantities or prices, and the auctioneer deciding on the clinching prices or quantities, respectively. The bidders of the auction can be the CPs or the SBSs, bidding for the requested caching contents. The auctioneer of the auction is the MNO allocating the caching placement and charging (paying) the caching money to the bidders.

3) Matching Theory: The caching allocation problem between the CPs and the MNO competing for the caching priority[2], or between the SBSs and the MNO competing for the caching placement can be viewed as a basic problem of resource allocation between the users and resources. The efficient algorithmic applications of matching theory make it possible for optimizing the self-organizing caching systems by accurately representing the objectives of different entities with the *preference relation* [14]. Specifically, the *many-to-one matching* and *many-to-*

[2]Caching priority: higher priority refers to more copies of files cached in SBSs of the MNO.

many matching, in which at least one player in one of the sets can be matched to multiple players of the opposite set, are most appropriate to deal with the problem of wireless caching networks. Here the caching price and copies of files cached in each SBS are the key parameters determining the matching solution.

4) Contract Theory: The contract theory studies the contractual arrangements of economic actors in the presence of asymmetric information. An incentive contract mechanism can be designed to allow the MNO to offer a contract to each CP. The information asymmetry might capture several hidden information such as the willingness of the CPs to cache their contents and the traffic generated by the users of the CPs which is unknown to the MNO.

5) Bayesian Game: Bayesian game is defined as a game when the information about other players such as their payoffs is incomplete to at least one of the players in the game. Under the "common prior assumption", a Bayesian game can be converted into games of complete but imperfect information. In the current context, the incomplete information includes incomplete caching access probability and partial information about the caching capacity.

C. Game Solution Concepts and Analysis

Now we will provide the basic solution concepts for the proposed game models and analyze the appropriate algorithms to derive the solutions for the different caching scenarios. The best response (BR) and NE are typical solution concepts in game theory. The Stackelberg equilibrium (SE) provides ideas when further consider the Stackelberg game. Moreover, the incentive-oriented pricing mechanisms not only affect the revenue in the upper application layer, but also influences the resource allocation in the physical layer in modern wireless systems such as the wireless edge caching networks. Other relevant solution concepts for different game models are listed as well in the following.

1) Best Response: In game theory, the BR is the strategy (or strategies) which produces the most favorable outcome for a player, taking other players' strategies as given [15]. Provided the utility U_m of a player m in the caching game $\mathcal{G}$ mentioned above in different contexts, the BR strategy (the caching prices or the optimal quantity of caching files) is solved by $S_m^{BR} = \arg\max_{S_m} U_m(S_m, \boldsymbol{S}_{-m}^{BR}), \forall m \in \mathcal{M}$, where $\boldsymbol{S}_{-m}$ denotes the strategies of all the other players except player m in the proposed game. The BR is the key concept in deriving the NE of the non-cooperative game, mentioned as follows.

2) NE and generalized Nash equilibrium (GNE): In game theory, the NE is a solution concept of a non-cooperative game involving two or more players, in which each player reacts with the BR to other players. A strategy profile $\mathbf{S}^*$ is a NE of the caching game $\mathcal{G}$ if

$$\begin{aligned} \mathbf{S}_m^* &\in \mathcal{S}_m(\mathbf{S}_{-m}^*), \qquad \forall m \in \mathcal{M}, \\ U_m(\mathbf{S}^*) &\geq U_m(\mathbf{S}_m, \mathbf{S}_{-m}^*), \quad \forall \mathbf{S}_m \in \mathcal{S}_m(\mathbf{S}_{-m}^*). \end{aligned} \tag{1}$$

At the NE, no player can gain additional utility by changing its own strategy unilaterally given the other players' strategies fixed.

3) Prices in Games: Prices are comprehensively investigated in the resource allocation problems of wireless networks. The outcome NE of a non-cooperative game without pricing in fact usually leads to an inefficient operating point. Therefore, the properly designed prices of caching unit plays an important role of balancing the caching requests and the limited caching capacity. By deciding the optimal prices, the caching resources can be fully exploited. Pricing mechanisms can be universally applied in various game models for caching-enabled wireless networks.

4) Stackelberg Equilibrium: The SE is formulated by the BR of the followers of the Stackelberg game and the BR of the leader by predicting the strategies of the followers. In the caching scenario regarding the economic incentives, the leader solves the caching price and the followers solve the requested quantities of caching files.

5) Stability: The concept of stability is important for various solutions in game theory, such as the NE and the matching between the resources and users. The basic solution concept for a matching problem is the *two-sided stable matching*, if and only if there is no blocking pair (BP). We define a BP for a stable marriage case as a pair of resource and user denoted by (r, u), if u prefers r than its currently matched resource i and r prefers u to its currently matched user j. Then u will leave i for r. Similarly, the resource r will match to the user u. The definition of this stability is universal to all types of matching problems.

6) Incentive Compatibility: A mechanism is called incentive compatible if every participant in a game can achieve his/her best outcome just by acting according to his/her true preferences. This can be accomplished by careful price design so that all the players report their true information such as the access probability of the contents, the QoS requirements of the mobile users and the caching capacity of each SBS.

III. Current Approaches and Research Challenges

In this section, we review various wireless caching scenarios modeled by game theory in the perspective of business incentives. Based on the current game frameworks, the potential research directions are further discussed and the possible game models and solution concepts can be pursued. In Table I, we summarize the suitable game models that can be utilized to deal with the conflict and cooperation problems among these caching-enabled entities. The corresponding solution concepts and the algorithms implementation are characterized as well.

Given Table I, we now interpret in detail some remaining research challenges related to the caching-enabled wireless systems and the potential game models to solve these problems.

Incomplete Information. One challenge of the future research on wireless caching is the problem with incomplete information. This information includes the CSI between the caching entities and the wireless users that require the caching contents, the access probability of each caching content, the caching capacity of each SBS, and etc. Bayesian games are appropriate fashions to deal with these caching problems with incomplete information.

Heterogeneity of Types. Another challenge remains in the heterogeneity of the entity types. These entities are the CPs, the SBSs and also the wireless users, respectively. The differentiated willingness of all entity types for caching based on different parameters, the heterogeneous QoS requirements of the wireless users that require the caching contents and the caching cost levels for the consumed power and the backhaul transmission, should be considered as incentives for motivating wireless caching.

Topology on Caching. The topology of various entities involved in the wireless caching system plays an important role in the design of the caching policies. The geographical distribution of the SBSs as the caching components certainly influences the caching placement resolutions and cost/price optimization, the delay of downloading the caching contents and the strategy of the backhaul transmission. Stochastic geometry can be utilized on top of the game models for caching [2].

Cooperation and Competition among CPs/SBSs. When multiple MNOs or SBSs exist in the caching system, the competition for attracting more CPs or higher payments for caching can be expected. The noncooperative game and the resulting NE can be applied for deciding the caching prices in the competitive scenario. Cooperation like coalitions may also be formed to maximize the utilities of MNOs or SBSs by setting the payoff strategies to reduce the caching cost, the backhaul cost with exchange data. The strategic interactions among CPs/SBSs are beneficial to the CPs as well with caching payment decrease.

Physical Layer Management. The physical layer analysis of the caching systems involves the topics of transmit power allocation from the backhaul for caching, the interference management when multiple caching requests are made simultaneously and the cost of caching given the limited caching capacities. All these physical layer resolutions and strategies of different entities in the caching system will react in the upper layer revenues of the wireless caching system and vice versa. Game theory has been successfully applied in communication technologies, notably in those related to physical layer resource allocation. For example, the non-cooperative game can be applied to allocate the transmit power for caching in a distributive manner and the Stackelberg game is appropriate for the interference control.

Security and Truthful Behavior. In all wireless systems, the physical layer security is an essential issue to be investigated. Mechanism design should be investigated on the purpose of preventing the potential misbehavior of the players in the caching framework. An efficient caching mechanism in the perspective of business incentives requires the truthful performance of all the caching participants. The CPs, SBSs or MNOs may manipulate the pricing and caching process by revealing wrong information about themselves. Punishment prices on cheating players, or the classical Vichzey-Clarke-Groves (VCG) mechanism can be applied to prevent the misbehavior of potential cheaters by motivating them to reveal their truthful information in the proposed games.

Privacy and Commercial Market of Caching Statistics. The statistics of caching preferences or the access probability are confidential to CPs and mobile users. These statistics can make profit for different caching entities and therefore influence the incentive mechanisms of caching such as the pricing policy. The CPs are typically concerned with their private information that could be leaked from the caching contents. This commercially important information includes user identities, data access probabilities and sensitive commercial data like user preferences. Data anonymity, artificial noises in the caching contents and coalitions of various CPs can be applied to avoid the privacy threats.

However, privacy preservation may result in poor accuracy of the caching deployment. How to protect the caching privacy and utilize the caching statistics, and therefore benefit the interests of all parties, become a very important issue in future wireless edge caching networks. Game models such as bargaining and contract theory can be adopted to deal with the tradeoff when considering the commercial market of the caching statistics.

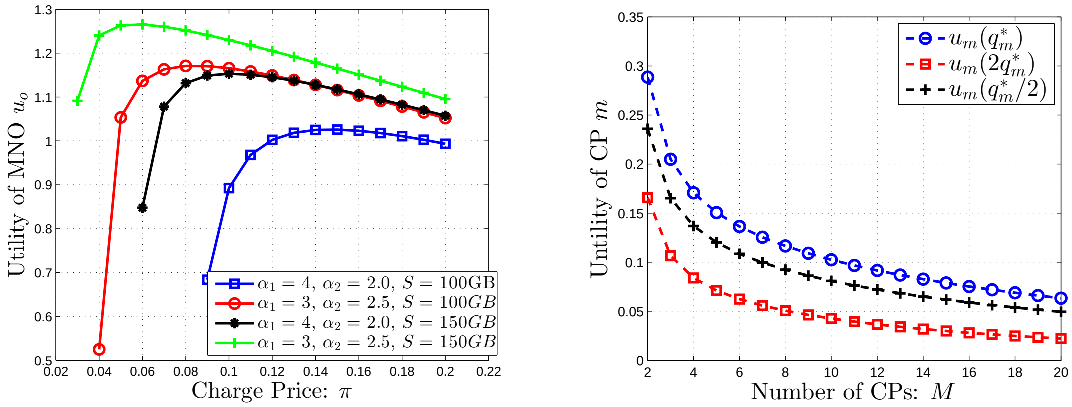
Table I: Caching-enabled systems modeled as games.

Caching entities (players)	Game models	Solution concepts	Algorithms	Related works
CPs, MNO	Stackerlberg game, non-cooperative game	SE, NE, price	Best response dynamic (BRD), optimization theory	[4]
CPs, MNO	Stackerlberg game, Contract theory	SE, Incentive compatibility (IC), price	optimization theory	[12]
CPs, MNO, users	Stackerlberg game	SE, price	Non-convex optimization, stochastic geometry	[9]
D2Ds, MNO	Stackerlberg game, non-cooperative game	SE, NE	BRD, optimization theory	[5]
users, MNO	Stackerlberg game, non-cooperative game	SE, NE, price	BRD, optimization theory	[7]
SBSs, CPs, users	Matching game	Stability, price	Matching algorithm	[10]
SBSs, CPs, MNO	Stackerlberg game, non-cooperative game, Bargaining	SE, NE, price	BRD, optimization theory, bargaining algorithm	
SBSs, MNO	Auction	bid, price, caching quantities	optimization theory	
SBSs, government, MNO	Stackerlberg game, Auction, Bargaining	bid, price	optimization theory	

Table II: Technical challenges and potential solutions.

Research challenges	Key elements	Potential game models
Incomplete information	CSI, access probability, caching capacity	Bayesian games
Heterogeneity of types	QoS, willingness of caching, caching preferences	Bargaining games, Auction
Topology on caching	SBS, users	Bargaining games
Physical layer management	power, interference	Stackelberg game, non-cooperative game
Security and truthful behavior	content, statistics of caching	Mechanism design, bargaining
Commercial market and privacy	content trading, price policy	Contract theory, heterogeneous prices Data anonymity with coalition

In Table II, we provide an overview of the research challenges of the caching problems and their potential solutions modeled as multiple games. After shedding light on the existing and potential research problems in the business side of the wireless caching from a game theoretical point of view, we now focus on a case study in the following section. More technical and comprehensive details of this case study can be found in [4].



(a) (b)

Figure 2: Numerical results for the proposed Stackelberg game with (a) utility function of the MNO with respect to charge price π for 2-CP case, and (b) utility of the CP with respect to the total number of CPs M under different caching requests.

IV. Case Study: A Stackelberg Game for Incentive Proactive Caching Mechanisms

Suppose a proactive caching scenario for an HetNet, with N cache-enabled SBSs managed by one MNO. Consider a Stackelberg game in order to deal with the caching incentive problem, where a non-cooperative game is considered as a sub-game among all the M CPs. The MNO is considered as the leader of the game which provides the caching price π to all the CPs, whereas the CPs are the followers in which they react with their optimal quantities of contents to cache given the price π. Both the MNO and the CPs are rational and optimize their own utilities denoted by U_o and U_m, respectively. In this scenario, the caching price π is the strategy of the leader MNO, and the quantities of caching contents $q_m(\pi), \forall m$ are the strategies of the followers CPs. Assuming that the access probability of each content is perfectly known at the MNO and CPs, the M CPs compete with each other for potential caching quantities, given the limited storage capacity S at the SBSs. Each CP in this condition choses to cache the first q_m^*-most popular contents.

The revenue of the MNO in the caching problem is the total charge summed up from all the CPs for caching their contents, which is a function of the caching price π and the quantity of caching request from all the CPs, denoted by $\mathbf{q} = [q_1, \ldots, q_M]$. Given the utilities in the non-cooperative sub-game, the CPs optimize their strategies of the quantity of the caching requests and provide them to the MNO provided the charge price π declared by the MNO. The optimal q_m^* can be obtained by solving the following problem:

$$q_m^* = \arg\max_{\mathbf{q}} U_m(\pi) \quad \text{subject to} \quad \mathbf{q} \geq 0. \tag{2}$$

The solution of the non-cooperative game is the NE caching quantities after playing the BR dynamics by jointly solving problem (2) for all $m \in \mathcal{M}$. After predicting the quantity requests of the CPs, the MNO optimizes the charge price π by solving the following problem:

$$\pi^* = \arg\max_{\pi} U_o(\mathbf{q}(\pi)) \quad \text{subject to} \quad \pi \geq 0. \tag{3}$$

As a result, both the utilities of the MNO and the CPs are maximized in the proposed Stackelberg game for the incentive proactive caching mechanism.

Numerical results are given to illustrate how Stackelberg game works to improve the wireless caching system in respective of incentives. Without loss of generality, we consider a simulation scenario of one MNO and 2 CPs, with identical content size as $10GB$ for high quality videos.

Fig. 2a depicts the utility function of the MNO with respect to the charge price as its strategy, where α is the amount of generated requests by the users of CP m. It can be seen that the proposed utility of the MNO always admits a global optimum for different sets of parameters. The utilities of the MNO with more caching capacity are higher. This is due to the fact that more content requests can be served and less caching cost is spent for the same amount of caching contents. The difference of the starting points of the curves are due to the feasible price region. Given the optimum price, the utility of the MNO yields even up to 50% higher gains than arbitrary chosen prices.

Fig. 2b shows the utility of a single CP with respect to the total number of CPs M while the quantity of the caching request q_m changes. The optimal quantity q_m^* is derived accordingly. The charge price is given as the optimal price π^* for different total number of CPs. The utilities with double quantity $2q_m^*$ and half quantity $\frac{q_m^*}{2}$ are given for comparison, respectively. We note that the more CPs, the lower the utility U_m of each CP. This is due to the increasing number of CPs which results in the increase of the amount of the requested storage space and therefore, a higher price is charged by the MNO. Additionally, the utility of each CP decreases when the total storage capacity allocated for the other CPs increases. We can also observe that by requesting the optimal caching quantity q_m^*, each CP achieves 20% higher utility than requesting $\frac{q_m^*}{2}$ and up to 50% than requesting $2q_m^*$.

V. Conclusions

In this article, we explored the current edge caching models from the business perspective considering the behavior of multiple caching entities and proposed the applications of game theory on heterogeneous wireless edge scenarios enabled with caching for future 5G networks. We have discussed existing literature and future research challenges associated with the wireless edge caching. The case study we considered has highlighted the gains of these approaches, showing a great potential of game-theoretical models for incentive caching mechanisms in edge communication networks.

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