Game Theoretic Approaches for Wireless Proactive Caching

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ABSTRACT

Recently proposed wireless proactive caching has opened up a promising avenue for reducing the redundant traffic load of the future wireless network. In addition to infrastructure updating, caching schemes for different wireless caching scenarios are also essential problems of concern. Along with the benefits brought by proactive caching, the cost of proactive caching should also be taken into account, since caching schemes can be influenced by different interest relevant parties in wireless networks. In this article, we discuss several typical caching scenarios and apply corresponding game theoretical models to illustrate how the selfishness of different parties may influence the overall wireless proactive caching. Efficient caching strategies can be designed by carefully considering the relations and interactions among these parties by using game theory. We also outline possible future research directions in this emerging area.

INTRODUCTION

With recent improvements in mobile communication technologies, an increasing number of users are attracted to diversified online services when using mobile devices, which leads to explosive demands for mobile data. Recent studies have shown that mobile video streaming accounts for 50 percent of mobile data traffic, which is currently still growing rapidly. As a result, the excessive demand for data is draining the limited spectrum resources of wireless transmissions, especially the wireless link between base stations and users, and the wireless backhual link between base stations and the core network.

To cope with this problem, a promising solution is to cache popular contents at the edge of mobile networks (e.g., base stations, access points, or even users' mobile devices) [1]. In this way, the number of duplicate content transmissions can be greatly reduced, and real-time transmissions can be accelerated. Due to the recent development of learning techniques, the popularity of contents (i.e., the demand for different contents) can be predicted by tracking users' requesting frequency and analyzing historical data [2]. This advantage improves caching efficiency by pre-downloading popular contents during off-peak times and serving predictable peak-hour demands, which is referred to as *proactive caching* [2]. With a proper proactive caching strategy, not only can the heavy traffic load be relieved at peak hours, but also the request latency can be decreased, which results in better user experience. Although dozens of techniques can be implemented to improve proactive caching, such as network coding [3] and multicasting [4], a systematic study on the interactions among different parties related to wireless proactive caching is still lacking.

In the architecture of wireless networks, multiple-interest relevant parties exist, which usually consist of the service providers (SPs) who provide contents to download, the mobile network operators (MNOs) who manage the facilities of the radio access network (RAN), and the mobile users who wish to enjoy different contents [5]. Different parties have their own benefits when applying a specific caching strategy, and their benefits could conflict with each other. For instance, caching more contents into the storage of base stations may bring more profit for users. But this could also jeopardize the benefit of the MNOs who manage the base stations, due to the cost of additional power consumption and occupying limited caching storage. Since each party only cares about its own profit, it is necessary to analyze the interactions among these parties and design proper solutions. To this end, game theory can be adopted as an effective tool to deal with such problems.

In this article, we apply game-theoretical approaches to model and analyze the problems that may arise in the typical scenarios of proactive caching in wireless networks. Different benefits and costs for different parties are taken into account, and the conflicts of interests among different parties are also considered. Specifically, we provide four representative scenarios of wireless proactive caching and discuss them with different game theoretical approaches.

Based on the structure of the considered wireless network, we further classify the scenarios of proactive caching into two categories: *centralized wireless networks* and *distributed wireless networks*. In the former category, the contents from SPs are cached into the storage of wireless facilities in RANs owned by MNOs. Either the SPs or the MNOs carefully design caching schemes based on the demands for contents in a central-

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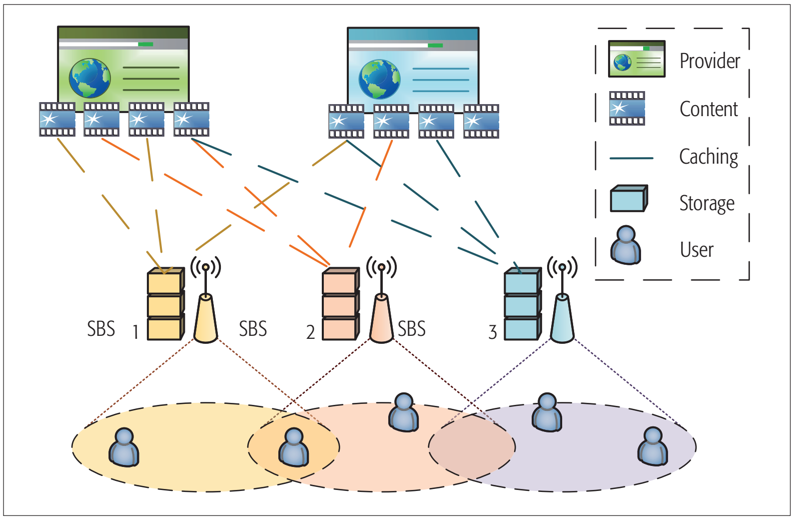

Figure 1. The system model of small cell base station caching.

ized manner. In the latter, popular contents are cached in cache-enabled mobile devices. Mobile users who own such devices can determine whether to cache contents for other users in a distributed manner. The relation of these two categories also lies in the architecture of wireless caching [1], where the centralized one has a higher level, while the distributed one is closer to mobile users who enjoy the contents in the end.

For proactive caching in centralized wireless networks, we consider two representative scenarios. The first one is referred to as *small cell base station* (SBS) *caching*, where multiple SPs aim to cache their own contents into SBSs. The limited caching storage results in competition among SPs, so we use an *auction game* to solve the problem. The second one is referred to as *roadside unit* (RSU) *caching*, where MNOs pre-download the specific contents for onboard users (OBUs, referring to users in moving vehicles) based on pre-determined driving routes. We apply a *contract game* to design pricing strategies for different quality of service (QoS) levels of caching.

For proactive caching in distributed wireless networks, we also consider two representative scenarios. The first one is referred to as *device-to-device* (D2D) *caching*, where temporarily static users are distributed in the cellular networks and are able to communicate by D2D links (e.g., WiFi or Bluetooth). We adopt a *coalition game* to analyze whether and how a cooperative group can be formed to download contents together. The second one is referred to as *vehicle-to-vehicle* (V2V) *caching*, where OBUs are able to cache contents and communicate by V2V links. This scenario is different from the former one due to the random possibility of moving vehicles encountering each other. Therefore, we use an *evolutionary game* to analyze the willingness of different types of OBUs to join V2V caching. For the rest of this article, we first present four typical scenarios of wireless proactive caching. Then the corresponding game-theoretic approaches are provided. In addition, we give an example of SBS caching with more detailed evaluations. Finally, we present the future outlook for this area and conclude the article.

Typical Scenarios of Proactive Caching in Wireless Networks

In this section, we classify proactive caching scenarios into two categories based on the structure of the considered wireless network.

In each category, two typical scenarios are presented, which address the major concerns of the interactions among different parties or individuals.

Proactive Caching in Centralized Wireless Networks

In centralized wireless networks, the caching procedure is carried out by SPs or MNOs, and the caching strategies are usually designed in a centralized manner.

Considering different kinds of facilities in RANs that may be cache-enabled, we select two representative scenarios: SBS caching and RSU caching.

Small Cell Base Station Caching: Small cell base stations (SBSs) are considered as a promising infrastructure to deal with the rapidly increasing wireless traffic by achieving high-density spatial reuse of communication resources. However, the backhual link capacity of SBSs is the major obstruction to providing satisfactory download speed. By caching popular contents into the storage of SBSs, duplicate transmissions can be reduced, and heavy traffic can be alleviated. At the same time, users can experience better QoS (e.g., lower delay or download time) as they request contents. The system model of SBS caching is shown in Fig. 1.

For each SP who possesses a certain set of contents, the QoS of its own users is the major concern. Therefore, each SP has intentions to cache its contents into SBSs to improve the expectation of user experience. According to the average user density covered by each SBS and the popularity distribution of the contents, a certain SP, in general, would like to cache its most popular contents into the most popular SBSs. However, due to the existence of multiple SPs and the finiteness of caching storages, competition among SPs is unavoidable. How to effectively cope with the competition and simultaneously guarantee high overall user experience is a major concern.

Roadside Unit Caching: With the application of high-end facilities on vehicles and the deployment of RSUs, OBUs can resort to more resource-intensive online services, which may drain the limited wireless resources. One possible solution is to equip the RSUs with caching abilities, in which way contents requested by OBUs can be obtained without the crowded backhaul links from RSUs to the Internet [6]. Fortunately, the driving routes of OBUs can be pre-determined with the help of navigation software on mobile devices or cars. Therefore, OBUs can ask for pre-caching services from the MNO who manages the RSUs based on their driving routes, as shown in Fig. 2.

In an ideal situation where the driving speed and download speed can be predicted precisely, the MNO only needs to divide the specific content into segments and cache them sequentially in the SBSs along the route.[1] However, the practical situation makes it difficult to guarantee the continuity of downloading.

[1] To "cache sequentially" is to cope with the case where the content is streaming media, which needs to be downloaded and enjoyed at the same time.

By dividing the content into overlapping segments instead of independent ones, the possibility of keeping continuity can be increased against the uncertainty of driving speed or download speed. But this also leads to a higher storage occupation cost for the MNO. Note that there might be different types of OBUs who have different QoS demands. The MNO can provide different caching schemes for different QoS demands. Therefore, how to design a proper pricing strategy for different types of OBUs to guarantee the MNO's utility becomes the major concern in this scenario.

Proactive Caching in Distributed Wireless Networks

In the distributed wireless networks, caching procedure is carried out directly by each user, and the caching strategies are usually designed in a distributed manner. One important difference between caching in distributed and centralized wireless networks is: The distributed one can reduce the duplicate transmissions at the wireless downlink of RAN, in addition to those at the backhual link. In contrast, the centralized one can only reduce the duplicate transmissions at the backhual link since contents are cached in RAN. In the distributed wireless networks, we select two representative caching scenarios based on whether the users are temporarily static: Device-to-Device Caching and Vehicle-to-Vehicle Caching.

Device-to-Device Caching for Mobile Users: D2D communication is becoming more and more important in the future architecture of wireless communications, which provides direct high-speed short-range communications. Since the storage of mobile devices is becoming larger and cheaper, there is a possibility that mobile users can keep the contents that they have already watched/used/consumed and serve other nearby users who want the contents by D2D communications. In this way, cache-enabled user devices can be seen as distributed caching storage, which is an important supplement to the centralized proactive caching in cellular networks, as shown in Fig. 3.

Here, we consider users to be temporarily static (e.g., in an office or a cafe). Therefore, users are able to cooperatively download their commonly desired content, then cache and transmit it to each other through D2D communications. For each user, the download time can be shortened, and the power consumption of setting up cellular links can be reduced. However, the additional power consumption of caching and D2D communications still cannot be ignored. Whether the user can obtain a higher payoff by caching cooperatively depends on the utility of him/her joining each downloading group. Therefore, the major concern in this scenario is how to propose the strategy for users to form effective coalitions in a distributed way.

Vehicle-to-Vehicle Caching for Onboard Users: Although RSUs provide OBUs with better Internet connectivity, the high speed of vehicles and the limited downlink capacity of RSUs both make it hard to download all of the desired contents just by utilizing infrastructure-to-vehicle (I2V) communications. With the help of V2V communications, OBUs can transmit cached contents to other OBUs, or obtain cached copies from other nearby OBUs.

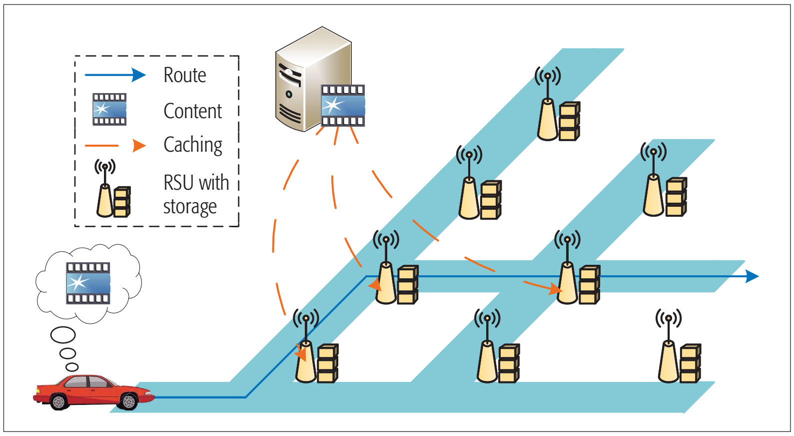

Figure 2. The system model of roadside unit caching.

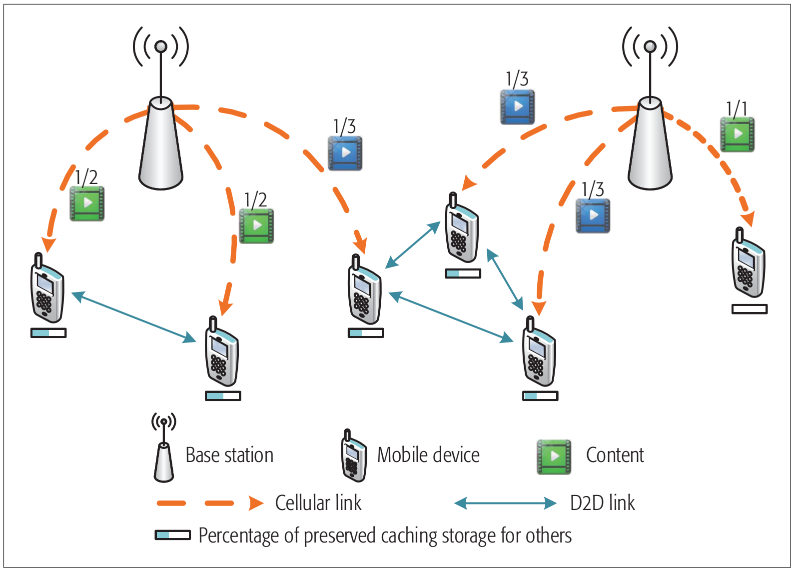

Figure 3. The system model of device-to-device caching.

Note that the major difference between D2D caching and V2V caching is the OBUs' mobile nature. Since the neighbors of a certain OBU may change stochastically with high frequency, cooperative caching and downloading are less effective than in the D2D caching scenario. Therefore, OBUs have to pre-determine whether to keep the contents after watching/using/consuming them. Whenever an OBU wants to download a content, the RSUs are able to help him/her by checking whether there is another nearby OBU who possesses the desired content.

However, free riders may exist in this scenario, that is, those who only ask for cached contents but never cache for others. A reasonable method to avoid the existence of free riders is to make a regulation like this: Only those users who participate in V2V caching can obtain cached contents from others, and the users who participate in V2V caching have to keep the contents in storage after watching/using/consuming them. This is actually an agreement that OBUs can decide whether to comply with, based on their own types (e.g., frequency of driving, frequency

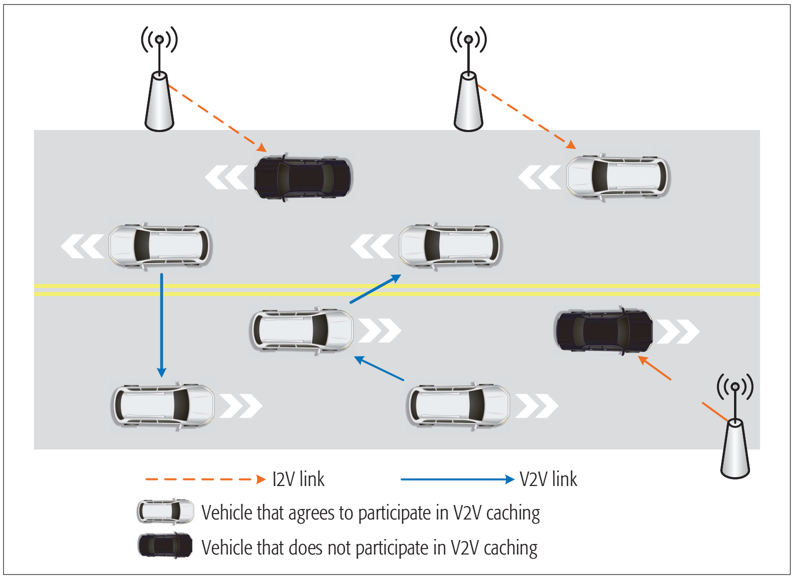

Figure 4. The system model of vehicle-to-vehicle caching.

of requesting contents) and the price of RSUs' help on notification of available caching.

The major concern is whether different types of OBUs are willing to participate in V2V caching. The system model is shown in Fig. 4.

Game Theoretic Approaches for Proactive Caching in Wireless Networks

Proactive Caching in Centralized Wireless Networks

Auction Game for Small Cell Base Station Caching: The auction game is a branch of game theory that has been widely used in trading if the prices of the commodities are undetermined [7]. Since there are usually not enough commodities for all of the potential buyers, the trading prices are determined by the competition among these potential buyers during the bidding procedure in the auction.

In the SBS caching scenario, each SP is able to predict the popularity of its content by analyzing historical data. Based on the users' requests from different SBSs, we also assume that the SP is aware of the user density within different coverage areas of SBSs. In this way, SPs can evaluate their contents while it is less possible for MNOs to know SPs' valuations. Therefore, an auction game is suitable in this scenario to determine the trading price through the competition among SPs [8]. In this setting, the storage of SBSs is considered as objects to be auctioned. If there is only one MNO, the auctioneer (the one who is in charge of the auction procedure) could be the MNO itself. If there are multiple MNOs, the auctioneer would probably be another third party with enough credit. Since the caching cost is imposed on MNOs who own the SBSs, the price determined in the auction should be paid to MNOs by SPs who obtain corresponding caching storage.

Given a fixed auction mechanism, each rational bidder (SP) aims to maximize it own profit by bidding properly. This means that the bids for objects are not guaranteed to be the same as valuations (depending on the specific auction mechanism). The Nash equilibrium bidding strategy for a certain bidder is the strategy that is the best response to others' current bidding strategies. Thus, the Nash equilibrium outcome can be seen as the outcome of a more practical situation for SBS caching. As depicted in the system model, the primary objective is to guarantee the caching efficiency (for better user experience), which means that a proper caching allocation should be accomplished by the auction mechanism.

Contract Game for Road-Side Unit Caching: In economics, the contract game studies how economic actors construct contractual arrangements, generally in the presence of asymmetric information [9]. One prominent application of the contract game is the design of optimal schemes for managerial compensation. For instance, the boss in a company does not know the types (e.g., hardworking or lazy) of his/her employees at first, and uniform treatment of different employees does not guarantee high workload for the boss. But by properly designing a workload–salary table, all rational employees are guaranteed to make their best choice, which can in turn maximize the total workload.

In RSU caching, OBUs who have pre-determined driving routes can ask for specific caching services. However, MNOs can provide different QoS of caching services, and different types of OBUs have different QoS demands. Although the exact type of each user is unknown to the MNO, the MNO is able to estimate the proportions of different types. Therefore, the contract game can be utilized by the MNO to design proper pricing strategies for different types of users in order to maximize its total payoff.

The main idea is to design a monopolist-dominated quality-price contract, which means that the MNO dominates the quality-price designing and wishes to maximize it own profit. To make the contract feasible, incentive compatibility and individual rationality are the two necessary and sufficient properties [10]. In this way, each OBU's best choice is to pay for the caching service designed for his/her type, and no OBUs can obtain more utility by not choosing caching services. Based on the above two principles, a contract can be designed to maximize the profit of the MNO.

Proactive Caching in Distributed Wireless Networks

Coalition Game for Device-to-Device Caching: The coalition game is a cooperative game where some of the players have intentions to form cooperative groups (i.e., coalitions) [11]. A coalition represents an agreement among the players to act as a single entity to get a higher payoff for each participant.

In the D2D caching scenario, depending on the specific caching strategy, each user device will suffer higher power consumption by using caching storage (depending on the size of the cached contents) or serving others through D2D communications (depending on the communication range). Since each user is only able to estimate its own utility (perhaps with the help of an application on the mobile device), how to effectively form D2D caching groups should be considered as a distributed problem. By means of the coalition game, we can analyze and predict

Typical proactive caching scenario	Category	Information assumptions	Major problem description	Solution	Payment
SBS caching	Centralized	SPs know their own valuations, while the MNOs do not know SPs' valuations.	Competition among multiple SPs for limited caching storage.	Auction game	SPs to MNOs
RSU caching	Centralized	OBUs know their own types, while the MNO knows the percentage of each type.	Optimal pricing for different user-specific caching QoS demands.	Contract game	Users to MNOs
D2D caching	Distributed	Users know their own types and their own preferences for contents.	The possibility of mobile users to download content cooperatively.	Coalition game	No payment
V2V caching	Distributed	OBUs know their own preferences and the nearby caching population.	The interdependent utility of participating V2V caching for selfish OBUs.	Evolutionary game	OBUs to MNOs (fixed charge)

Table 1. Game theoretic approaches for typical scenarios in wireless proactive caching.

how users will cooperate with each other in a distributed manner based on different conditions.

For a coalition game, the primary objective is to find stable outcomes. In a stable outcome, multiple coalitions with different sizes are expected to be formed by users. If a user can obtain the highest payoff in the current coalition, then the state for him/her is stable, otherwise he/her has the intention to leave the current coalition and join another one. For the user who has a low caching cost (which depends on the mobile device), he/she is more likely to cooperatively cache with others. In addition, if adjacent users have similar preferences for the contents, then a coalition is also expected to form. Generally speaking, D2D caching with coalition formation is able to reduce average download cost for mobile users.

Evolutionary Game for Vehicle-to-Vehicle Caching: The evolutionary game is the application of game theory to analyze how the proportions of different strategies in the population change [12]. The evolutionary game differs from classical game theory by focusing more on the dynamics of strategy variation, which is influenced by both the quality and proportion of the competing strategies in the population.

In the V2V caching scenario, only users who participate in V2V caching can obtain cached contents from others, and users who participate in V2V caching have to keep the contents in storage after watching/using/consuming them. We denote *caching population* as the proportion of OBUs who participate in V2V caching. Whether an OBU should participate in V2V caching depends not only on its his/her own type, but also on the caching population. If more OBUs participate in V2V caching, it is easier for a certain OBU to obtain a cached content. In addition, OBUs may change strategy based on the current caching population he/she estimates. Therefore, the evolutionary game can be utilized to analyze the time-variant feature of OBUs's strategies.

The major objective of applying the evolutionary game is to find evolutionary stable strategies. An evolutionary stable strategy is a mixed strategy for the whole population, such that the influence of a small proportion of other strategies will gradually disappear in the long-term evolution. For V2V caching, in particular, each type of OBU will have a certain possibility to choose whether he/she participates in V2V caching. Such a state is meaningful in both theoretical study and practical implementation. This is because the system can maintain stable caching performance against the turbulence induced by a small number of OBUs leaving or joining the system.

Table 1 summarizes the aforementioned four typical caching scenarios, their major problem descriptions, the information assumptions, and the corresponding kinds of game theory, along with the economic payment direction.

One Example: Multi-Object Auction for Small Cell Base Station Caching

In this section, we briefly introduce the multi-object auction, and then apply this method to solve the content storage allocation problem in SBS caching.

Basics of Multi-Object Auction

Auctions are being widely used in trading where the prices of commodities are determined by the competition among all the potential buyers during the bidding procedure. A multi-object auction is a special kind of auction that allocates multiple objects (instead of only one object) to multiple bidders in a single round of bidding. A multi-object auction can be classified into three categories, based on the relations of the objects in each round of auction [7]:

- *Independent objects*: The marginal utility of a certain object is not influenced by what objects the bidder has already owned.
- *Substitutable objects*: The marginal utility of a certain object is likely to decrease if another object is owned by the bidder.
- *Complementary objects*: The marginal utility of a certain object is likely to increase if another object is owned by the bidder.

We present below an example to show how a multi-object auction with substitutable objects can be applied to solve the caching problem in SBS caching.

Small Cell Base Station Caching by Multi-Object Auctions

As shown in Fig. 1, we study a small cell network which involves several MNOs that manage a number of overlapping SBSs and several SPs that own different sets of contents. If the content requested by a certain user is cached in one of its nearby SBSs, the request can be served by the SBS, which leads to a lower delay. Otherwise,

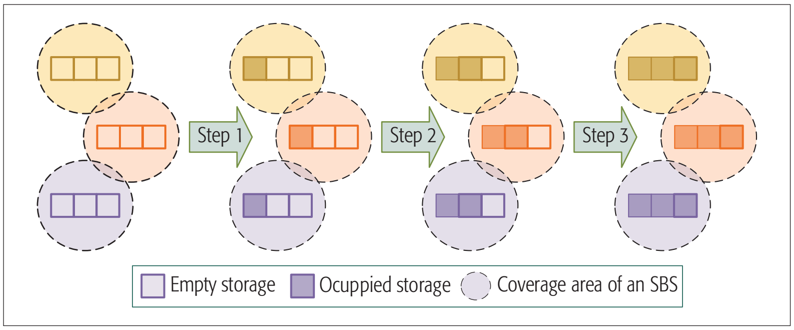

Figure 5. The proposed solution to complete one hour's caching. The provided example consists of three steps, where each step represents a multi-object auction that allocates contents to SBSs..

any one of the nearby SBSs can serve its request by setting up backhaul connections to the core network and downloading the content from servers. In a real-world situation, the average loads of SBSs are different at different hours of a day, and the speed-limited backhaul link of SBSs may suffer congestion during peak hours. The main objective is to minimize the overall average delay of content requests from users at each hour by properly designing the caching scheme. However, due to the overlapping regions among SBSs and the finiteness of caching storage, the optimal solution for this problem is NP-hard, indicating that the problem cannot be resolved by any algorithm with low time complexity.

The proposed caching scheme is carried out by holding a series of multi-object auctions,[2] where the storage blocks of SBSs are abstracted as objects and the contents of SPs are abstracted as bidders. Specifically, the caching allocation in each hour is determined by holding a series of *multi-object auctions* sequentially, where the *i*th storage blocks in all of the SBSs are auctioned off in the *i*th auction. This process is essentially to auction the storage of all SBSs concurrently in multiple steps,[3] as shown in Fig. 5.

The valuation of each bidder for each object is determined by the marginal utility of caching, that is, how much the average delay can be decreased by caching the content into the given SBS. Before each auction, the valuations of bidders for objects have to be updated according to the current caching allocation, since the marginal utility of each object for each bidder is not constant due to the overlapping of SBSs. In other words, the storage sizes of different SBSs are partly substitutable objects. In reality, SPs submit bids on behalf of its own contents based on their marginal utilities. After the auction is done, each SP obtains a certain amount of caching spaces of SBSs. Then contents can be cached into SBSs according to the auction result (which can be done automatically by its server).

For each multi-object auction, the market matching algorithm is adopted,[4] which takes the valuations as input, matches the bidders and objects, and outputs the allocation results and trading prices [13]. This algorithm starts by adding virtual objects to equalize the number of bidders and the number of objects. Then it tries to find a perfect matching between bidders and objects based on the preferences of bidders. If the perfect matching cannot be found, some of the prices of the objects will be increased in order to change the bidders' preferences. The algorithm is guaranteed to end with a perfect matching that shows the allocation of bidders (contents of SPs) and objects (storage blocks of SBSs).

To evaluate the performance, the proposed mechanism is carried out by simulations. Figure 6a shows how the average delay changes in a day. The outcome of the proposed mechanism greatly reduces average delay and also surpasses the highest popularity algorithm (which only caches the most popular contents in each SBS and is used as a benchmark here). Figure 6b shows the impact of the capacity of SBSs and the total number of contents. It can be observed that the same amount of storage capacity makes greater difference in a low-storage-capacity situation. In addition, a greater amount of contents makes it more difficult to achieve low latency.

Future Outlook

Proactive Caching in Heterogeneous Wireless Networks

One typical heterogenous wireless network can be a macrocell base station (MBS) along with its underlaid SBSs. Users can download content from the SBSs' caching storage directly (with the least delay), download content from the MBS's caching storage through the SBSs' backhual (with medium delay), or in the worst case, download content from the servers of the SPs (with the highest delay). This heterogenous architecture makes the caching problem difficult to analyze. Furthermore, if the MBS and SBSs have different owners, the interactions among SPs and MNOs become far more complicated. Since the profits brought by caching are divided among multiple parties, a bargaining game can be adopted to balance the benefits of different parties and achieve a stable outcome [14].

Proactive Caching in Wireless Relay Networks

In cache-enabled wireless relay networks, contents can be cached in the storage of wireless relays [15]. Relays can transmit data to users simultaneously with the base station; thus, the diversity of wireless transmissions can be improved. However, the base stations and relays could belong to different MNOs. The auction game can still be applied in this scenario since multiple SPs are willing to compete for finite caching storage of both base stations and relays. However, evaluation of contents should be carefully considered due to the complicated topology of the network.

Conclusion

In this article, game theoretical approaches have been introduced to model and analyze the cooperative and non-cooperative behaviors of different parties in wireless proactive caching. In centralized wireless networks, the auction game is used to resolve the competition among multiple SPs in the scenario of SBS caching, and the contract game is adopted to design the proper pricing strategy in the scenario of RSU caching. In distributed wireless networks, the coalition game is applied to analyze the possibility of cooperative caching in the scenario

[2] The reason for adopting multi-object auctions instead of single-object auctions is to reduce the total number of auctions held each hour. Since communications among SPs and MNOs need to be set up for the auction, reducing the total number of auctions can alleviate the cost induced by communications in practical implementations.

[3] Concurrently allocating the storage blocks of SBSs avoids the fairness problem that may arise in the multi-MNOs case.

[4] This algorithm itself guarantees truthfulness. But this property is lost when we regard each content as individual bidders, because one SP can own multiple contents, and its utility is the sum of all its contents' utilities. Nevertheless, we are able to prove that the total performance of caching is not degraded by "untruthful bidding," regardless of whether an SP knows others' valuations.

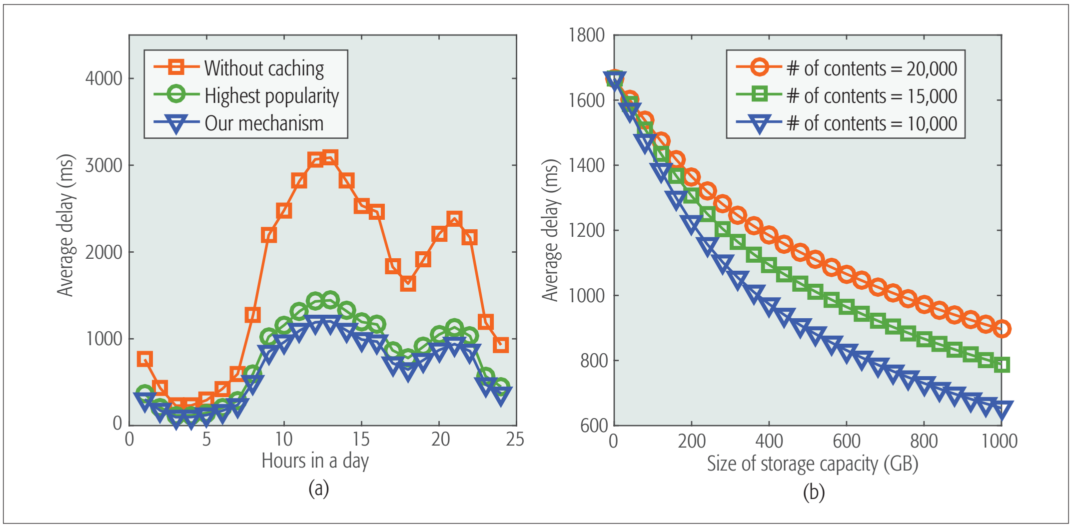

Figure 6. Simulation results: a) the delay variation in 24 hours, with or without caching; b) the influence of storage size and number of contents on caching performance.

One of the typical heterogenous wireless networks can be a macro-cell base station (MBS) along with its underlaid SBSs. Users can download content from the SBSs' caching storage directly (with the least delay), download content from the MBS's caching storage through the SBSs' backhual (with medium delay), or in the worst case, download content from the servers of the SPs (with the highest delay).

of D2D caching, and the evolutionary game is considered as a promising tool to analyze the behavior of users in V2V caching. A more detailed multi-object auction-based solution for the small cell caching scenario is presented. Possible future research directions of game-theory-based wireless proactive caching are also outlined.

Acknowledgments

This work was partially supported by the National 973 project under Grant 2013CB336700, by the National Nature Science Foundation of China under Grant U1301255, and by the National Natural Science Foundation of China (Project 61370056).

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