D2D-Enabled Wireless Caching using Stackelberg Game

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***Abstract*—Evidence indicates that wireless video traffic has played an important role in cellular networks. Device-to-device (D2D) enabled caching technology has been proposed to alleviate network backhaul traffic pressures, especially in peak hours. In this paper, a Stackelberg game is proposed to solve the interests' conflict in D2D-enabled wireless caching networks, where exist two kinds of users including subscribers and helpers. System model is characterized by a hierarchical structure, where the macro base station (MBS) optimizes its strategy based on the prices of helpers. Then, the optimal price and optimal power are derived in closed-forms. Simulations are carried out in three environments which include one helper, two helpers and three helpers in the network, respectively. In one-helper situation, the utilities of MBS and helper decrease as the distance increases. The tradeoffs between power and prices are presented in the simulation results of two-helpers and three-helpers situations. It can be seen that the utility of MBS is concave over power for the reasons that the increased profits are dominated firstly and then the cost substantially increases.**

I. Introduction

With the growing needs for entertainment and social connections, wireless video data have played an important role in cellular networks. It is predicted by Cisco that wireless video data will reach 75% of the total amount of data in 2020 [1]. Caching is a new technology proposed to reduce the traffic load by pre-allocating popular files in the networks [2–4]. Wireless data caching consists of two stages: data placement and data delivery. In the first stage, video data such as popular movies are transmitted to the small base stations during offpeak time. While in the second stage, subscribers will not request data from macro base station (MBS), instead they may request from small base stations which are adjacent to them. As such, caching in small base stations can help offload data flow from MBS. Recent studies have concentrated on the femto-caching problem [5–7]. However, there are some concerns about femto-caching, among which construction expenses and maintenance cost of small base stations are considered as the bottleneck to realize femto-caching.

The existing network architecture will not be able to satisfy the enormous data growth in the near future [8]. Researchers have proposed 5G technologies which include multi-carrier filter banks, millimeter wave technology, massive multiple input and multiple output (MIMO), super density heterogeneous network and device-to-device (D2D) technology, to fulfil the requirements of future communications [8–10]. Among 5G technologies, D2D technology will change the current communication manner where information communications between two subscribers in the same network rely on MBS. In addition, compare to femto-cell networks, D2D technology can achieve reuse gain, proximity gain and hop gain [11, 12].

D2D-enabled wireless caching networks where extra expenditures on the construction and maintenance are not necessary are attracting more and more researches recently. Ref. [13] proposes an optimal scheme for D2D networks to cache the popular video content. In this scheme, cluster size is optimized to reduce the transmission delay. Besides the transmission latency issues, the D2D-enabled caching networks should be coupled with many other issues. It is important to establish a reasonable incentive mechanism to stimulate users sharing files with others. Due to selfishness or some concerns such as battery duration or privacy problem, users usually are reluctant to participate in D2D communication without a rational policy. Game theory is an appropriate way to solve this kind of interests' conflict problem [14]. Ref. [15, 16] and [17] have made careful studies on this kind of problem in relay communications. Specifically, In [15] and [16], authors concentrate on the wireless multimedia quality optimization problem in D2D neworks where user's equipment is modeled as a leader and the BS is modeled as a follower. In [17], authors propose a distributed Stackelberg game over multiuser cooperative communication networks to achieve the optimal relay selection and power allocation without channel state information. The distributed relay nodes are regarded as leaders while the source node is modeled as a follower.

To this end, we are inspired to research on D2D-enabled caching networks from game theoretic perspective. The main contributions of this paper are as follows:

1) D2D-enabled wireless caching networks are proposed. In this network, there coexist two kinds of users including subscribers and helpers. Helpers who have pre-cached popular files in their local storages can assist MBS to transmit files.
2) Stackelberg game is proposed to solve the interests' conflict in the D2D-enabled wireless caching networks.
3) Optimal prices announced by helpers and optimal power bought by MBS are derived in closed-form. The optimal price is associated with the channel gain from helper to

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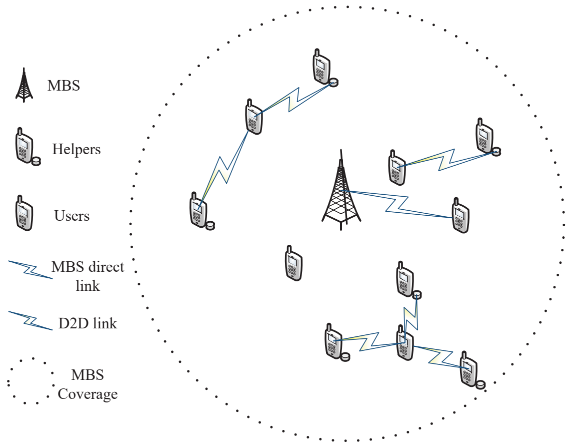

Fig. 1. System Model

subscriber. In a word, a high channel gain leads to a high price.

4) Simulation results are provided to demonstrate the interactions between helpers and show the tradeoffs of the MBS's utility in two-helpers and three-helpers situations. The utility curve of MBS is concave, that's because the increased data rate induced by the increased power is dominated of the utility at first, then the increased rate of payment exceeds the gain, leading to the descent of MBS's utility.

The rest of this paper is organized as follows: system model and problems are presented in section II. Optimal solutions using Stackelberg game are discussed in section III. Simulation results are analysed in section IV. And conclusions are drawn in section V.

II. System Model and Problem Formulation

In the D2D-enabled caching networks, communications are conducted in underlay cellular networks. MBS is assumed to know exactly the files cached in each D2D helper, so it can directly control helpers who are located around the requesting subscriber with few information exchanged. Helpers communicate over the orthogonal channels which are allocated by the MBS, so that no interferences exist between helpers.

A. System Model

We consider downlink communication in this paper. System model is depicted in Fig. 1. Heterogeneous networks (HetNet) consisting of a MBS and $\mathcal{H}$ D2D helpers are investigated. Files cached in helper i are presented as $\mathcal{F}_i$. Helpers who cache file n and assist MBS transmitting form the helpers set denoted as $\mathcal{H}_n$. And, there are N types of files in this network. Let $R_d(n)$ denotes the sum rate of transmitting file n from helpers in set $\mathcal{H}_n$, we have

$$R_d(n) = \frac{W}{|\mathcal{H}_n|}\log_2(1 + \sum_{i\in\mathcal{H}_n} \tau_i), \tag{1}$$

where τ_i is the signal to noise ratio (SNR) transmitted from helper i, it is defined as

$$\tau_i = \frac{P_i(n)G_{i,d}}{P_I + \sigma^2}. \tag{2}$$

W is the bandwidth sharing by helpers in $\mathcal{H}_n$. $P_i(n)$ is the transmission power from helper i. $G_{i,d}$ is the channel gain from helper i to destination user d. P_I is the average interference from MBSs and is treated as a fixed value in this paper. σ^2 is the noise power.

B. Problem Formulation

It is assumed that file allocation has been completed according to certain criteria in the off-peak time. Each helper has different files in its local caching. There are three steps to get a file in this HetNet.

Step1: Inquiry. A subscriber in this network requests MBS for a file. Its assumed that MBS controls the D2D communications and it knows the helpers who are caching the requested files. MBS broadcasts the participation inquiries. Then it collects the feedbacks from distributed helpers about whether they are willing to participate.

Step2: Game. Stackelberg Game is proposed to solve this problem. Leaders in this game are helpers who provide the price firstly. Follower MBS buys power from helpers who are willing to share files with others. For each requested file n, they perform the game once, in which they want to maximize their own utility, respectively. Users in the range for direct communications are incentive to cooperate for enhancing the transmission quality.

The utility function of MBS can be defined as

$$U_{\text{MBS}} = aR_d(n) - \sum_{i\in\mathcal{H}_n} b_i(n)P_i(n), \tag{3}$$

where a denotes the current gain per unit of rate, $b_i(n)$ is the fees per unit of power charged by helper i for transmitting file n. It can be observed that the higher the data rate, MBS can obtain more profits.

The utility function of helper i is defined as

$$U_i = (b_i(n) - c)\, P_i(n), \tag{4}$$

where c is the cost helpers need to spend in transmission data. Step 2 will be further discussed in the next section.

Step3: Transitions. Helpers, whose utility is less than zero, will not participate in transmission. Otherwise helpers will transmit files through orthogonal channels allocated by MBS.

III. Optimal Solution based on Game Theory

The optimization problem for MBS is to buy proper power that maximizes its utility, which can be formulated as

$$\max_{P_i(n)} U_{\text{MBS}}. \tag{5}$$

The optimization game for each helper is to ask a proper price not only to earn the payment that covers its prime cost but also gain as many profits as possible. The utility of helper i is defined as

$$\max_{b_i(n)} \quad U_i, \quad \text{s.t.} \;\; b_i(n) - c > 0, \tag{6}$$

where c is its prime cost. The utility of MBS is a concave function of $P_i(n)$, since we have

$$\frac{\partial^2 U_{\text{MBS}}}{\partial P_i(n)^2} = -\frac{aW}{\ln 2 \times |\mathcal{H}_n|} \times \frac{G_{i,d}^2}{(P_I + \sigma^2 + P_i(n) \times G_{i,d} + \sum\limits_{j \in \mathcal{H}_n \setminus i} \frac{P_j(n) \times G_{j,d}}{G_{i,d}})^2} < 0. \tag{7}$$

Let $\frac{\partial U_{\text{MBS}}}{\partial P_i(n)} = 0$ and $W' = \frac{aW}{\ln 2 \times |\mathcal{H}_n|}$, we have

$$\frac{\partial U_{\text{MBS}}}{\partial P_i(n)} = \frac{\partial \left(W' \ln(1 + \sum\limits_{i \in \mathcal{H}_n} \tau_i) - \sum\limits_{i \in \mathcal{H}_n} b_i(n) P_i(n) \right)}{\partial P_i(n)} = \frac{W' \frac{G_{i,d}}{P_I + \sigma^2}}{1 + \sum\limits_{i \in \mathcal{H}_n} \tau_i} - b_i(n) = 0. \tag{8}$$

Then we arrive at

$$P_i^*(n) = \frac{W'}{b_i(n)} - \sum_{j \in \mathcal{H}_n \setminus i} \frac{P_j(n) \times G_{j,d}}{G_{i,d}} - \frac{P_I + \sigma^2}{G_{i,d}}. \tag{9}$$

It can be observed that, the optimal power bought from helper i is a function of price $b_i(n)$. By substituting $P_i^*(n)$ into U_i in Equation (4), and letting $\frac{\partial U_i}{\partial b_i(n)} = 0$, $B = \sum\limits_{j \in \mathcal{H}_n \setminus i} \frac{P_j(n) \times G_{j,d}}{G_{i,d}} + \frac{P_I + \sigma^2}{G_{i,d}}$, we have

$$\frac{\partial U_i}{\partial b_i(n)} = \frac{\partial \left[(b_i(n) - c) \times \left(\frac{W'}{b_i(n)} - B \right) \right]}{\partial b_i(n)} = \frac{W' c}{b_i^2(n)} - B = 0, \tag{10}$$

then we get

$$b_i^*(n) = \sqrt{\frac{cW'}{B}}. \tag{11}$$

It can be observed that the optimal price is associated with its channel gain. The higher the channel gain, the higher price it can declare. However, the optimal power in Equation (9) is affected not only by the optimal price but also by other helpers' power.

IV. Simulation and Analysis

In this section, we evaluate the performance of the proposed network model. Simulations are conducted in three environments which consist of one helper, two helpers and three helpers, respectively. Bandwidth W is assumed to be 1MHz, carrier frequency is 2GHz, Noise power is 10^{-8}w, a is 0.01,

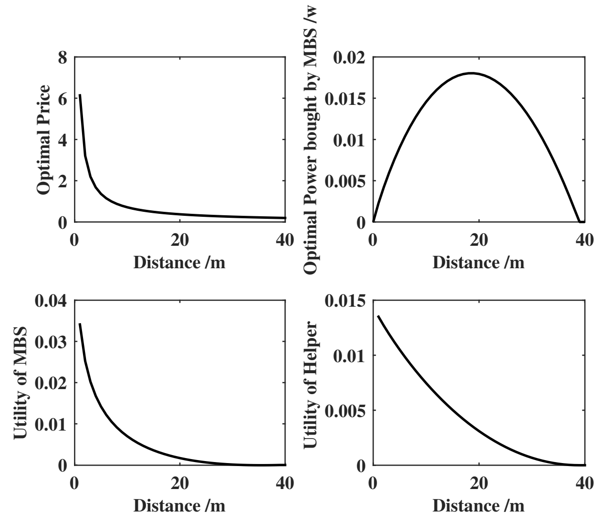

Fig. 2. One-helper situation

c is 0.2 and P_I is equal to 0.1×10^{-8}w, D2D link is modeled according to WINNER II which is defined as,

$$\sigma_k = -18.7 \log_{10}(D) - 20 \log_{10}(f_c/5) - 46.8 + 3\varphi, \tag{12}$$

where σ_k is the path loss in dB, D is the distance in meters, f_c is the carrier frequency in GHz and φ is a zero-mean unit variance Gaussian random variable modeling lognormal shadow fading.

In Fig. 2, there is only one helper who has cached the requested files. The distance between the helper and destination is assumed to vary from 0 to 40m. It can be seen that the optimal price it declares is decreasing along with the distance increases. Firstly, the optimal power bought by MBS is increasing as the price decreases, because more power leads to more data rate, and hence more profits. However, as the distance keeps increasing, the optimal power decreases for the reason that there are less benefits from employing helpers to transmit files. The utility functions of both helper and MBS decrease as the distance increases.

In Fig. 3, there are two helpers H_1 and H_2, who are 20m and 15m away from the destination, respectively. When power bought from H_1 varies from 0.0001w to 0.02w, the optimal price of H_2 is determined according to Equation (11). It can be seen from Fig. 3 that when MBS buys more power from H_1, less power will be bought from H_2 even though H_2 lowers its price. Hence the utility of H_2 is decreasing. The utility curve of MBS is concave in this case. The increased data rate induced by the increased power bought from H_1 is dominated at first so that the utility of MBS rises at the beginning. Then the increasing rate of payment exceeds that of the gain, leading to the descent of MBS's utility at certain point.

In Fig. 4, there are three helpers. The distances between helpers and destination are all 15m. Power bought from H_1 is 0.001w and 0.0005w from H_2, respectively. As varying the power bought from H_3 in the range of 0.00001w and 0.01w, the optimal prices of H_1 and H_2 decrease. The two

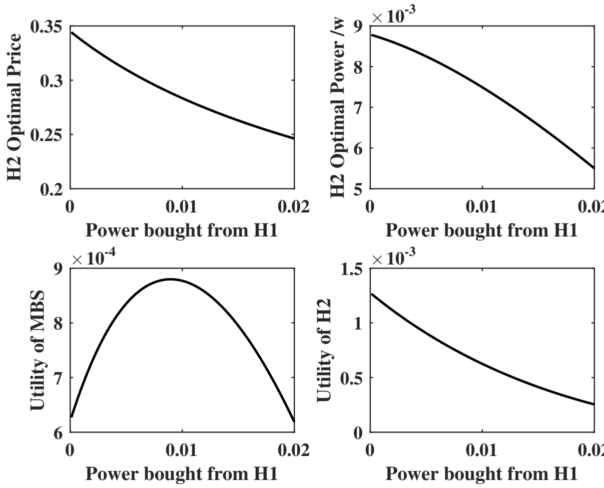

Fig. 3. Two-helpers situation

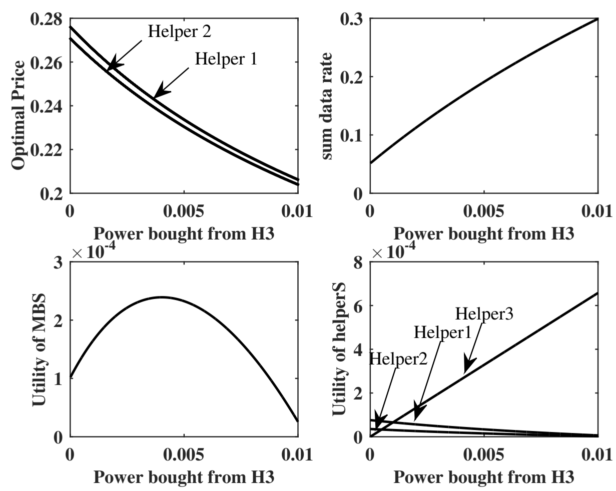

Fig. 4. Three-helpers situation

helpers both want to sell more power by reducing their prices. The utility of MBS is also concave in this case. Since the accumulated data rate of helpers ascends, the utility of MBS goes up at first. However, it starts to decline while the cost increment gets bigger.

Likewise, in three-helpers situation, we change the distance between destination and helper 3 from 15m to 18m. As the distance increases, it can be seen from Fig. 5 that the utility of MBS begins to shrink. We can get a conclusion that when power bought from a helper are fixed, MBS may earn more utility from a helper who is close to the destination.

V. Conclusion

In this paper, we analysis optimal prices set by helpers and power bought by MBS in D2D-enabled caching networks. MBS arrange helpers who have requested files in their caching to assist in transmission. Stackelberg game is proposed to solve this kind of problem in this paper. In this game, helpers need to

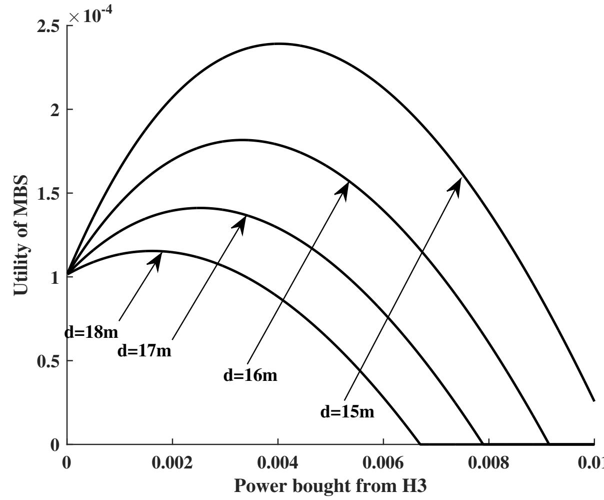

Fig. 5. The utility of MBS when Helper 3 in different positions

evaluate proper prices to maximize their own interests, while MBS wants to tradeoff between power and the data rate. That is more power high data rate, and hence more profits, leading to more payments. It is shown in simulations that the utility of MBS increases at first because of the increased data rates, and then decreases because of the increased cost.

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