ISSN 2383-630X(Print) / ISSN 2383-6296(Online)
Journal of KIISE, Vol. 44, No. 8, pp. 854-859, 2017. 8
https://doi.org/10.5626/JOK.2017.44.8.854

게임이론 기반 무선 통신에서의 캐시 할당 기법
(Game Theoretic Cache Allocation Scheme in Wireless Networks)

트라 후옹 티 리 † (Tra Huong Thi Le) 김 도 현 † (Do Hyeon Kim) 홍 충 선 †† (Choong Seon Hong)

요 약 기지국(Base Station)에서 인기있는 콘텐츠(비디오)를 캐싱하는 것은 전송 대기 시간을 줄일 수 있는 효율적인 방법이다. 본 논문에서는 콘텐츠 제공자(CP)가 캐싱 절차에 참여하도록 동기를 부여하기 위해 무선 네트워크에서의 사전 인센티브 캐시 메커니즘을 제안한다. 하나 이상의 Infrastructure Provider(InP)와 많은 CP로 구성되어 있는 시스템에서, InP는 InP의 기지국에서 캐시하는 파일 수를 결정하기 위해 CP가 경쟁하는 동안 수익을 극대화할 수 있도록 CP에 청구되는 가격을 정의하는 것을 목표로 한다. 또한 InP와 CP는 Stackelberg 게임이론 내에서 각각 선도자와 추종자로 정의된다. Backward Induction을 기반으로, 각 CP가 각 기지국에서 임대한 캐시 공간의 양을 정확하게 측정한 후, 최적화 문제를 해결함으로써 InP가 각 CP를 임대하는 가격을 계산한다. 이것은 비 균일 가격 체계를 고려한 점에서 기존 연구와 차이가 있다. 수치 결과는 제안 된 방법을 통해 InP의 이익이 균일 가격 책정보다 높다는 것을 보여준다.
키워드: 캐시 할당, 스태클버그 게임, 비균등 가격체계, 중첩 커버리지

Abstract Caching popular videos in the storage of base stations is an efficient method to reduce the transmission latency. This paper proposes an incentive proactive cache mechanism in the wireless network to motivate the content providers (CPs) to participate in the caching procedure. The system consists of one/many Infrastructure Provider (InP) and many CPs. The InP aims to define the price it charges the CPs to maximize its revenue while the CPs compete to determine the number of files they cache at the InP's base stations (BSs). We conceive this system within the framework of Stackelberg game where InP is considered as the leader and CPs are the followers. By using backward induction, we show closed form of the amount of cache space that each CP renting on each base station and then solve the optimization problem to calculate the price that InP leases each CP. This is different from the existing works in that we consider the non-uniform pricing scheme. The numerical results show that InP's profit in the proposed scheme is higher than in the uniform pricing.
Keywords: cache allocation, Stackelberg game, non-uniform, overlapped coverage

· This research was supported by Basic Science Research Program through National Research Foundation of Korea(NRF) funded by the Ministry of Education(NRF-2014R1A2A2A01005900)
· 이 논문은 제43회 동계학술발표회에서 'A Non-Uniform Pricing Scheme for Caching in Wireless Networks'의 제목으로 발표된 논문을 확장한 것임

† 학생회원 : 경희대학교 컴퓨터공학과
huong_tra25@khu.ac.kr
doma@khu.ac.kr
†† 종신회원 : 경희대학교 컴퓨터공학과 교수(Kyung Hee Univ.)
cshong@khu.ac.kr
(Corresponding author임)

논문접수 : 2017년 1월 23일
(Received 23 January 2017)
논문수정 : 2017년 5월 13일
(Revised 13 May 2017)
심사완료 : 2017년 5월 30일
(Accepted 30 May 2017)

정보과학회논문지 제44권 제8호(2017. 8)

1. 서 론

With the recent improvement in mobile communication technologies, demand on diversified online service increases rapidly. This leads to explosive growth of mobile data when using mobile devices. The problem is that there is a limited resource of wireless transmission, especially the wireless backhaul capacity.

To deal with the problem, an effective way is to cache popular files at the base station (BS) [1]. Moreover, not only the Infrastructure Provider (InP), who owns BSs can make a profit by leasing cache space at its BSs but also Content Provider (CP) can make more profit while providing the faster traffic. In the commercial cache system, each party (InP, CP) has their own benefit when applying specific caching strategy, price strategy, and their benefit could conflict with each other. For instance, the cache capacity at BS is limited, as a result, CPs compete for the possible caching quantities while maximizing their owned utility. InP has to offer the price mechanism so as to maximize its utility and incentive the CP to participate in the caching procedure. Another fact is the high density of BSs generates multiple overlapped areas, making the caching process among different BSs of different InPs need to be designed jointly.

Since each party in the commercial caching system only cares about its own profit, it is necessary to analyze the interactions among these parties and design a proper solution. Stackelberg game is applied widely in solving resource allocation in wireless network [2,3,6]. In [2], the authors considered model caching problem in device to device (D2D) network as a Stackelberg game in which the BSs are the leaders and the users are the followers. In this model, the BSs start by predicting users' reactions and determine the optimal price that maximizes their offloaded traffic from to the users' devices. With the rewards received from SBSs, users can then decide whether to help the SBSs by caching the files and participating D2D transmission or not. In [3], the authors also used Stackelberg game to propose a new cache incentive mechanism between one mobile network operator (MNO) and multiple CPs. However, they just considered the scenario where MNO set the uniform price on CPs. In this paper, we consider the non-uniform price mechanism and compare with the uniform one.

In this paper, we consider commercial caching system including one/many InP, several CPs. We provide two representative scenarios of a caching system and discuss them. The first scenario is the system of one InP and several CPs. We maximize system within using Stackelberg game framework in which InP is a leader and CPs are followers. Moreover, in the second scenario, we also consider the general scenario where there are many InPs provide cache space service to CPs. We consider when the coverage areas of BSs of different InPs are overlapping. And to demonstrate the competition between InPs, we assume that each CP has the limited budget in renting cache space.

The rest of this paper is organized as follows. Section 2 describes the system model. Section 3 presents Stackelberg game as an approach for one InP and many CPs with complete information. In section 4 we consider the multi- leaders multi-followers Stackelberg game. Section 5 provides the simulation results and Section 6 concludes the paper.

2. System Model

2.1 Network Model

We consider commercial caching system consists of $M=\{1,2,\cdots,M\}$ InPs and the set of $K=\{1,2,\cdots K\}$ CPs. InP m owns I_m BSs. Each BS can cache at most Q files. The coverage areas of BSs of the same of InP is non-overlapping, but the one of different InPs could be overlapping.

2.2 Proactive Caching

We assume that each CP has local content catalog F_k with F_k files. The global files catalog is denoted as $F=UF_k$. All files assumed to have the same size.

We assume that local popular of customer of CP k follow a power law [4] defined as:

$$p_k(f,n_k)=\begin{cases}(n_k-1)f^{-n_k}, & f\geq 1\\ 0, & f<1\end{cases}$$

Where f is a point in the support of the corresponding content and $n_k>1$ is the steepness of distribution curve of local popular of customer of CP k.

There are some certain types of files are more frequently requested than others, such as popular TV shows, blockbusters. So proactive the most popular contents caching is an efficient way to reduce the traffic transferred from the server to users.

We denote that CP k rent cache capacity of f_k files of each SBS of InP, the probability that content request by the CP k's customer fall in the range [0, f_k] is

$$h_k = \int_0^{f_k} p_k(f, n_k) df = 1 - f_k^{1-n_k}$$

3. Stackelberg Game with one InP, many CPs with complete information

3.1 Optimization Formulation of CP

Renting cache space from InP gives CP utility is a function of hit ratio U(h_k). Additionally, CP k pays money for renting cache from InP. If we denote s_k as the price that InP offers for CP. The payment of CP k is

$$s_k \log f_k$$

Where s_k is the price that InP offer for CP k. We choose function *log* as a way to incentive renting because the payment decreases when the amount of demanded renting increases. The *log* function was used to calculate utility in some existing work such as [5].

Therefore, depending on specific price that InP charge to CP for renting, CP will decide how much cache to rent to maximize its total utility.

$$\begin{aligned} &\max: w_k(1 - f_k^{1-n_k}) - s_k \log s_k \\ &s.t: \ f_k \geq 0 \end{aligned} \qquad (1)$$

3.2 Optimization Formulation of InP

The utility of InP is the income from leasing cache. InP has to find optimal price vector s ={$s_1, s_2, \cdots, s_k$} for maximize its utility

$$\begin{aligned} &\max: \sum_{k=1}^{K} s_k \log f_k, \\ &s.t: \sum_{k=1}^{K} f_k \leq Q, \\ &s_k \geq 0. \end{aligned} \qquad (2)$$

3.3 Stackelberg Equilibrium

Problem (1), (2) together form a Stackelberg game. The objective of this game is to find the Stackelberg Equilibrium (SE) points from which neither the leader (InP) nor the followers (CPs) have incentives to deviate.

Definition 1: Let s^*={$s_1^*, s_2^*, \cdots, s_k^*$} be a solution for problem (2), and f_k^*be a solution for problem (2), $\forall k$. Define f^*={ $f_1^*, f_2^*, \cdots, f_k^*$}. Then the point ($s^*, f^*$) is an SE for the proposed Stackelberg game if for any (s, f) with s≥ 0and f≥0, the following conditions are satisfied:

$$\begin{aligned} &P(s^*, f^*) \geq P(s, f^*) \\ &C_k(s^*, f_k^*) \geq C_k(s^*, f_k), \forall k. \end{aligned}$$

To find equilibrium, we need to first find the best response functions of the followers, based on which, we solve the best response function for the leader.

We can get the solution for (1) as follow:

$$f_k^* = \sqrt[n_k - 1]{\frac{n_k - 1}{s_k}} > 0$$

Here, for simplicity, we set w_k=1. Replace f_k^* into the problem (2), we have

$$\begin{aligned} &\max_{s_k}: U = \sum_{k=1}^{K} \left(s_k \log H_k - \frac{s_k \log s_k}{n_k - 1} \right) \\ &s.t: \sum_{k=1}^{K} H_k s_k^{-\frac{1}{n_k - 1}} \leq Q \\ &s_k \geq 0 \\ &H_k = (n_k - 1)^{\frac{1}{n_k - 1}} is\, a\, constant \end{aligned} \qquad (3)$$

The Hessian matrix of U is given:

$$HU_{K \times K} = \begin{vmatrix} \frac{1}{s_1(n_1 - 1)} & \cdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \cdots & \frac{}{s_K(n_K - 1)} \end{vmatrix}$$

We have $z^T HUz > 0$ with z is the arbitrary nonzeros vector, so the objective function of problem (3) is a concave function. Therefore (3) is a concave optimization, we can find the optimal solution. We can solve (3) by using the solver fmincon in Matlab.

4. Multi leader multi follower Stackelberg game

In this section, we consider the scenario where there is a set of M InPs M={1,2,⋯,M} lease a set of K CPs with cache space. Here, InP not only has the incentive pricing mechanism to motivate the CP to rent its cache space but also compete with other InPs to get more CPs as renting customers. To demonstrate for the competition among InPs, we add one more constrain which is the budget of each CP. Another addition in this section is that because of overlapping coverage area of BSs, the amount of renting cache space at different BSs of each CP are different with each other.

When InPs are not coordinated with each other, they can make decisions in a distributed manner, i.e. InP *m* is supposed to set its price $s^m=\{s^m_1, s^m_2, \cdots, s^m_K\}$ to all CPs for renting InP's cache space. InP not only should predict the reaction of all CPs $f^m=\{f^m_1, f^m_2, \cdots, f^m_K\}$ but also needs to consider the behaviors of the other InPs s^{-m} in order to receive satisfying revenues. Therefore, the optimization problem of the InP *m* is

$$\max_{s^m}: U_m\left(s^m \mid s^{-m,*}, f^{m,*}\right) = \sum_{i\in I_m}\sum_k s^m_k \log\left(f^{i,m}_m\right)$$
$$s.t: \quad s^* \geq 0 \tag{4}$$

Where $s^* = [s^{1,*}, s^{2,*}, \ldots, s^{M,*}]$ is the set of the optimal pricing strategies of all InPs. $s^{-m,*}$ is the set of the optimal strategies of all other InP except the InP *m*. $f^{i,m}_k$ is the renting cache space of CP *k* at BS *i* of InP *m*.

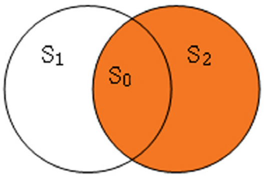

Fig. 1 overlapping BSs

For example, we have two BS with their coverage area illustrate in figure 1. If CP *k* rent f_1 quantity of BS1 and rent f_2 quantity of BS2 ($f_1>f_2$). The area S1 has hit ratio h_1, area S2 has hit ratio h_2 and the overlapping area S_0 has ratio h_2 because $h_2>h_1$. Therefore, the optimization problem for CP *k* satisfies:

$$\max: C_k\left(f^{i,m}_k \mid s^*_k\right) =$$
$$\sum_m\sum_{i\in I_m}\left(\Omega_i w_k\left(1-\left(f^{i,m}_k\right)^{-n_k+1}\right)\right)+$$
$$\sum_{O_j}\Delta_{O_j} w_k \max_{h\in O_j}\left\{1-\left(f^{i,m}_k\right)^{-n_k+1}\right\}$$
$$-\sum_m\sum_{i\in I_m} s^m_k \log\left(f^{i,m}_k\right)$$
$$s.t: \ f^{i,m}_k \geq 0$$
$$\sum_m\sum_{i\in I_m}\left(s^m_k \log\left(f^{i,m}_k\right)\right) \leq P \tag{5}$$

where $f^{i,m}_k$ denotes the cache capacity that CP *k* rent from BS *i* of InP *m*. Ω_i is the non – overlapping area of BS *i*, O_j is one set of BS overlapped with each other. Δ_{O_j} is the overlapped area of O_j. *P* is the budget of CP k.

In order to analyze the problem, we model the scenario as multi-leader multi-follower Stackelberg game [6], where InPs are leaders and CPs are followers. Similar to the section 3 we adopt backward induction to analyze the problem.

4.1 The strategy of renting cache space for CPs

By introducing the variable t_{O_j}, we can rewrite the problem (5) as followed:

$$\max: C_k\left(f^{i,m}_k \mid s^*_k\right) =$$
$$\sum_m\sum_{i\in I_m}\left(\Omega_i w_k\left(1-\left(f^{i,m}_k\right)^{-n_k+1}\right)\right)+$$
$$\sum_{O_j}\Delta_{O_j} w_k t_{O_j} - \sum_m\sum_{i\in I_m} s^m_k \log\left(f^{i,m}_k\right)$$
$$s.t: \ f^{i,m}_k \geq 0$$
$$\sum_m\sum_{i\in I_m}\left(s^m_k \log\left(f^{i,m}_k\right)\right) \leq P$$
$$\left\{1-\left(f^{i,m}_k\right)^{-n_k+1}\right\} \leq t_{O_j}, \forall h\in O_j$$

By introducing the dual variable λ, *a*, the Lagrange function of problem (5) is

$$L_k\left(f^{i,m}_k, \lambda_k, a^k_{hj}\right) = \sum_m\sum_{i\in I_m}\left(\Omega_i w_k\left(1-\left(f^{i,m}_k\right)^{-n_k+1}\right)\right)$$
$$+\sum_{O_j}\Delta_{O_j} w_k t_{O_j} - \sum_m\sum_{i\in I_m} s^m_k \log\left(f^{i,m}_k\right)$$
$$+\lambda_k\left(\sum_m\sum_{i\in I_m}\left(s^m_k \log\left(f^{i,m}_k\right)\right) - P\right)$$
$$-\sum_{O_j}\sum_{h\in O_j} a^k_{hj}\left(t-\left(1-\left(f^{i,m}_k\right)^{-n_k+1}\right)\right)$$

According to KTT condition, we have the best response of the CP k for InP m:

$$f^{i,m}_k\left(s^m_k\right) = \sqrt[n_k-1]{\frac{\left(\Omega_i + \sum_{O_j \mid i\in O_j} a^k_{ij}\right) w_k\left(n_k-1\right)}{\left(1+\lambda_k\right)s^m_k}}$$

4.2 Game analysis of InPs as leaders

Based on the predictions on all CPs' optimal strategies, the optimization of InP *m*, $\forall m \in M$

$$\max_{s^m}:$$
$$\sum_{i\in I_m, k}\left(\frac{s^m_k}{n_k-1} log\left(\frac{\left(\Omega_i + \sum_{O_j \mid i\in O_j} a^k_{ij}\right) w_k\left(n_k-1\right)}{\left(1+\lambda_k\right)s^m_k}\right)\right)$$
$$s.t: s^m_k \geq 0, \forall k\in K \tag{6}$$
$$\sum_k\left(\sqrt[n_k-1]{\frac{\left(\Omega_i + \sum_{O_j \mid i\in O_j} a^k_{ij}\right) w_k\left(n_k-1\right)}{\left(1+\lambda_k\right)s^m_k}}\right) \leq Q.$$

We adopt the sub-gradient method for pricing strategies of InPs. The method is as follow table 1:

4.3 Existence and Uniqueness of SE for the proposed game

By take the Hessian matrix of utility of CP k, we can proof that utility is a concave function. Therefore, there exists a unique best response for CP *k*.

Table 1 Algorithm for solving the price strategies of the InPs

Initially, we have $\lambda^{(0)}$, $a^{(0)}$

While $|\lambda_k^{(n)} - \lambda_k^{(n-1)}| \geq \epsilon, |a_{O_j}^{(n)} - a_{O_j}^{(n-1)}| \geq \delta$

  For InP m do

    Solve the problem (6)

  End For

  For CP k do

    Based on the price set by all InPs, each CP determines the optimal cache capacity to rent $f_k = \{f^1{}_k, f^2{}_{k,\cdots,} f^M{}_k\}$

    Update the dual variable

    $\lambda_k^{(n+1)} = \lambda_k^{(n)} - \Delta_k^n (P - \sum_m \sum_{i \in I_m} (s_k^m \log(f_k^{i,m}))$

    $a_{hj}^{k^{(n+1)}} = a_{hj}^{k^{(n)}} + \Delta_k^n \left(1 - (f_k^{i,m})^{1-n_k}\right)$

  End For

End While

Besides, the utility of InP is also an concave function, so InP has unique optimal price. In addition, the convergence of the sub-gradient algorithm has proved in [7].

5. Numerical Results

In this part, we show some numerical results. Figure 2, 3 show the individual CP performance. We choose the storage size of each SBS is 100, and the CPs are arranged according to their steepness in popularity distribution in which CP1 has the lowest steepness and CP8 has the highest one. When the steepness n has the lower value, then content popularity distribution corresponds to a more uniform distribution. This is the reason why CP with the lower n will rent more cache capacity as shown in figure 2. In figure 3, as a motivating way, InP offers the lower price for higher renting CP. Figure 4 show the utility of InP in two pricing scheme when the cache capacity at each BS changes. It is showed that the non-uniform price is better than uniform price when the storage capacity of each SBS varies. In figure 5, the total utility of InPs is shown as the coverage ratio increases from 0 to 37.5. As the overlapping ratio increases, the overlapping coverage increases. This leads to decreasing the renting cache at BS. In other words, the total utility of InPs decreases. When the budget of CPs increases, the total utility of InPs increases. Futhermore, we also see that the total utility of InPs in the non-uniform scheme are higher than in the uniform scheme with the same budget and overlapping ratio.

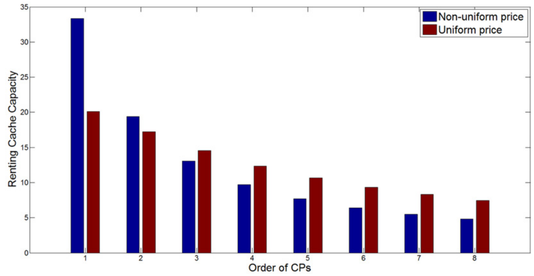

Fig. 2 Renting Cache Capacity of each CP

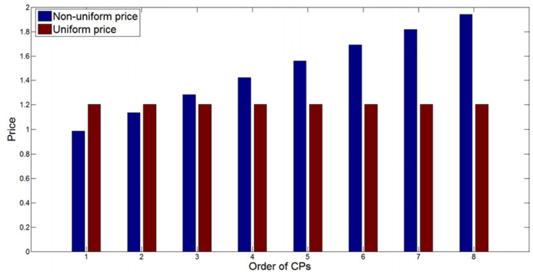

Fig. 3 Price offering for each CP

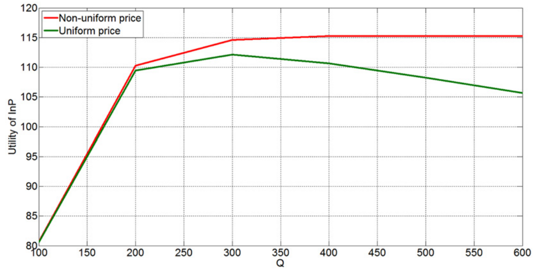

Fig. 4 Utility of InP

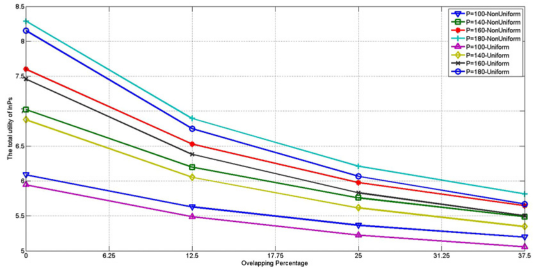

Fig. 5 Total Utilities of InPs vs. Overlapping ratio

6. Conclusions

In this paper, we considered a commercial caching system consisting of an InP and multiple CPs, where the InP leases its SBSs to the CPs for gaining profits while the CPs, after storing popular videos to the rented SBSs' cache, can increase the hit ratio. We proposed Stackelberg game theoretic framework and investigated the equilibrium. Moreover, we analyzed the system with many InPs and CPs. Finally, we showed some numerical results of CP's individual performance and comparison utility of InP in non-uniform and uniform pricing scheme. By applying the non-uniform prices scheme, we also investigate the change of total utility of InP indifferent budget and different overlapping area.

References

[1] N. Golrezaei, A. Molisch, A. Dimakis, and G. Caire, "Femtocaching and device-to-device collaboration: A new architecture for wireless video distribution," *IEEE Commun. Mag.*, Vol. 51, No. 4, pp. 142-149, Apr. 2013.

[2] Z. Chen, Y. Liu, B. Zhou, and M. Tao, "Caching Incentive Design in Wireless D2D Networks: A Stackelberg Game Approach," *IEEE ICC 2016*, Kuala Lumpur, Malaysia, 2016.

[3] FeiShen et al., "A Stackelberg Game for Incentive Proactive Caching Mechanisms in Wireless Networks," *GlobeCom 2016*, Washington DC, USA, Dec. 2016.

[4] B. Perabathini et al., "Caching on the edge: a green perpective for 5G networks," *IEEE ICC 2015*, London, UK, Jun. 2015.

[5] Mao Yang et al., "Opportunistic Spectrum Sharing based Resource Allocation for Wireless Virtualization," *7th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, Taichung, Taiwan, 2013.

[6] Nguyen Duy Duong et al., "Stackelberg Bayesian Game for Power Allocation in Two-Tier Networks," *IEEE Transactions on Vehicular Technology*, Vol. 65, No. 4, Apr. 2016.

[7] S. P. Boyd and L. Vandenberghe, "Convex optimization," Cambridge University Press, 2004.

Tra Huong Thi Le She received her B.S. and M.S. degrees in electrical-electronics engineering from Ho Chi Minh City University of Technology, Ho Chi Minh city, Vietnam, in 2010 and 2012, respectively. She is currently working toward her PhD degree at the department of computer science and engineering, Kyung Hee University. Her research interests include resource management, game theory

Do Hyeon Kim He received his B.S. degree in communication engineering from Jeju National University, in 2014 and his M.S. degree from Kyung Hee University in 2017. He is currently working toward his PhD degree at the department of computer science and engineering, Kyung Hee University. His research interests include SDN/NFV

홍 충 선
정보과학회논문지
제 44 권 제 1 호 참조