# A Non-Uniform Pricing Scheme for Caching in Wireless Networks

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Abstract

Caching popular videos in the storage of base stations is an efficient technology for reducing the transmission latency. In this paper, an incentive proactive cache mechanism in wireless network is proposed, in order to motivate the content providers (CPs) to participate in the caching procedure. The system consists of one 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 small base stations. 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 leasing for each CP. Different from the existing works, we consider the non-uniform pricing scheme. The numerical result shows that InP's profit in the proposed scheme is higher than in the uniform one.

## 1. Introduction

With the growth of mobile traffic, an effective way is Small Base Station (SBS) deployment, which makes cell smaller and the distance to user shorter. Besides bandwidth, the resource belongs to SBS is cache space[1]. So Infrastructure provider (InP), who owns SBS, can make profit by leasing cache space at its SBSs. On the other hand, Content Providers (CPs) who do not have cache and just have central servers in the core network, which is farther from CPs' customers. If CPs provide faster traffic, they can make more profit. To get that, CPs have to rent the cache space from InP. In this case, if the file requested by customer is cached at SBS, file can be served directly from SBS. Otherwise, customer is redirected to CP's central server for downloading through capacity limited backhaul. .

The problem is that cache capacity at SBS is limited. So CPs have to compete for the possible caching quantities while maximizing their owned utility. In addition, InP has to offer the price mechanism so as to maximize its utility and utilize its cache.

Stackelberg game is applied widely in solving resource allocation in wireless network. In [2], the authors considered model caching problem in D2D network as a Stackelberg game in which the SBSs are the leaders and the users are the followers. In this model, the SBSs 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 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 include one InP, several CPs. We maximize system within using Stackelberg game framework in which InP is leader and CPs are followers. The InP sets the price of leasing an cache, while the CPs compete with each other for renting a fraction of the storage capacity of SBSs.

The rest of this paper is organized as follows. Section 2 describes the system model. Section 3 presents Stackelberg game as an approach. Section 4 provides the simulation results and Section 5 concludes the paper.

## 2. System Model

### a. Network Model

We consider commercial caching system consists of one InP and the set of K={1,2,⋯K} CPs. InP owns SBSs. Each SBS can cache at most Q files.

b. Proactive Caching

We assume that each CP has local content catalog $F_m$ with $F_m$ files. The global files catalog is denoted $F=UF_m$. 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 a true that there are curtain type of files are more popular than other, such as popular TV shows, blockbusters, the case of videos with millions views. In addition, in cellular networks, the average of number of requests are much lower in wired network. So proactive the most popular contents caching is an efficient way.

We assume that CP rent the same storage capacity of each SBS. 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

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

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

$$=1-f_k^{1-n_k}$$

## 3. Stackelberg Game

a. Optimization Formulation of CP

The customers can download the videos either from the memories of the SBSs directly or from the servers of the CP at backbone networks via back-haul channels. In the first case, renting cache space from InP gives CP utility is a function of hit ratio $U(h_k)$. We choose linear function $U(h_k)=w_k h_k$, where $w_k$ is the weight of CP 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.

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

$$\max: w_k(1-f_k^{1-n_k})-s_k\log f_k$$
$$\text{st:}\quad f_k\geq 0 \qquad (1)$$

b. 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

$$\max: \sum_k s_k\log f_k$$
$$\text{s.t: } \sum_k f_k\leq Q$$
$$s_k\geq 0 \qquad (2)$$

c. 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 $\mathbf{f}^*=\{f_1^*,f_2^*,\cdots,f_k^*\}$.Then the point ($s^*$, $\mathbf{f}^*$) is an SE for the proposed Stackelberg game if for any (**s**, **f**) with **s** ≥ 0 and **f** ≥ 0, the following conditions are satisfied:

$$P(s^*,f^*)\geq P(s,f^*)$$
$$C_k(s^*,f_k^*)\geq C_k(s^*,f_k),\forall k$$

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.

To solve problem (1), we take the first derivative of objective function and set it equal 0. We can get the solution for (1) as follow:

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

Replace $f_k^*$ into the problem (2), we have

$$\max: \sum_k s_k\log H_k-\frac{s_k\log s_k}{n_k-1}$$
$$\text{s.t: } \sum_k H_k s_k^{-\frac{1}{n_k-1}}\leq Q$$
$$s_k\geq 0$$
$$H_k=(n_k-1)^{\frac{1}{n_k-1}} \text{ is a constant} \qquad (3)$$

We can see that the objective function of problem (3) is a concave function. Therefore we can solve (3) by using the solver fmincon in Matlab.

## 4. Numerical Results

In this part, we show some numerical results. Figure 1, 2 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 1. In figure 2, as an motivating way, InP offers the lower price for higher renting CP. Figure 3 show the utility of InP in two pricing scheme. It is showed that the non-uniform price is better than uniform price when storage capacity of each SBS varies.

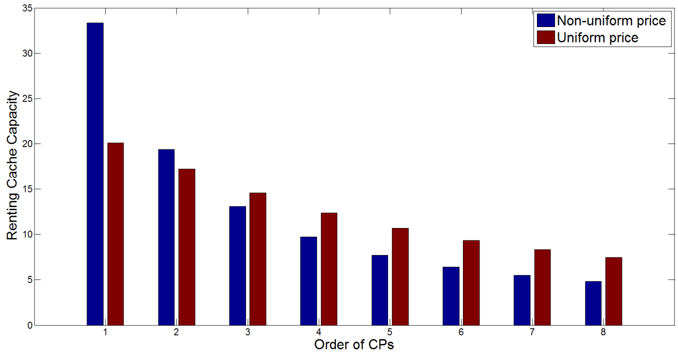


Figure 1: Renting Cache Capacity of each CP

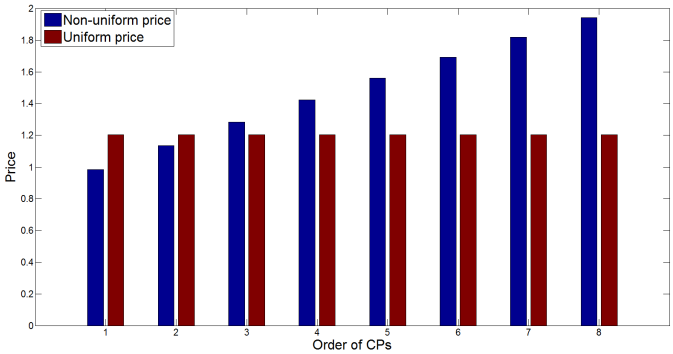


Figure 2: Price offering for each CP

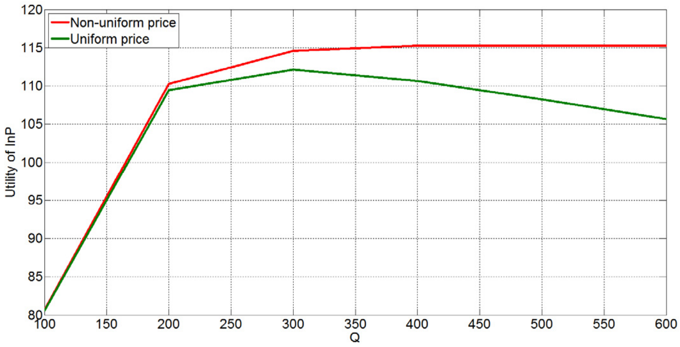


Figure 3: Utility of InP

## 5. 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 propose Stackelberg game theoretic framework and investigate the equilibrium. Finally, we show some numerical results of CP's individual performance and comparison utility of InP in non-uniform and uniform pricing scheme.

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