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Caching strategies and economic optimization in mobile networks

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Abstract

Storage resources and caching techniques permeate almost all areas of communication networks today. In the near future, caching will play an important role in storage-assisted Internet architectures, information-centric networks and wireless systems, reducing operating and capital expenses and improving services for consumers. users. In light of the remarkable growth in data traffic and the growing number of multimedia applications, the impact of caching is expected to become even deeper than it is today. In this article, we look at the economics of caching popular content. After modeling the cooperation between content providers and internet service providers as a coalition game, we assess the investments and benefits of both types of actors in caching strategies.

Keywords: caching, game theory, Shaplay,

1. INTRODUCTION

Caching has been considered to improve the delivery of content in wireless networks [1]. There is a growing consensus that improving network capacity by increasing the rate of access to the physical layer or densely deploying base stations is an expensive approach, and also being overtaken by the rapid increase in availability. mobile data traffic [2]. Caching techniques promise to fill this gap, and several interesting ideas have been suggested for this purpose: (i) deep caching at the advanced kernel level of packets (EPC) to reduce the delivery time of content [3]; (ii) caching at base stations to reduce congestion on their limited rate link links [7]; (iii) caching at the mobile device level to leverage device-to-device communications [8]; and (iv) coded caching to speed up transmissions over a broadcast medium [9].

Most of this work does not address the economics of investing and profiting from caching popular content in the ISP's network.

We overcome this limitation by simulating the investments and profits of content providers and ISPs as they cooperate in a coalition game to develop the optimal caching strategy.

2. PROBLEM STATMENT

a) Case of one ISP and one CP

We consider a scenario with an ISP which serves J users and a CP which offers additional content (movies, sports, education, etc.) to these users (see Fig. 1). Let N be the number of articles that the CP sells and P the price of an article. Each user j (1≤j≤J) pays the ISP access fee and the item fee requested to the CP.

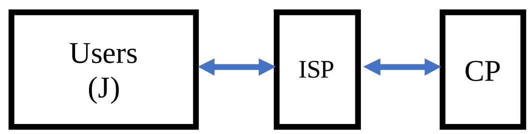

Fig. 1 : scenario of one ISP and one CP

In the absence of a cache in the ISP network, the utility of the CP, noted by UCP, is given by:

$$U_{CP} = DP - O \qquad (1)$$

Where D is the total number of requests for the N articles of the J users;

O constitutes operational expenditure;

The utility of the ISP, denoted by UISP, is given by:

$$U_{ISP} = \sum_{j=1}^{J} \pi_j - Bb \qquad (2)$$

Where π_j represents the network access charge paid to the ISP by user j;

B is the backhaul bandwidth necessary to serve the D user requests for the contents of the CP;

b is the cost of one unit of bandwidth.

By introducing caches in the ISP network (see fig. 2), three changes take place in the model :

- There is a cache deployment cost equal to sC where C is the capacity of the cache and s the price of a unit of capacity;

- The total number of requests in this case becomes D^C, which is due to the fact that the request is based on the perceived Quality of Experience (QoE) of users and considering that the ISP proactively stores the most content. popular:

$$D^C = (1 + \Delta)D \quad (3)$$

The parameter Δ corresponds to a QoE factor that reflects the change in demand for the contents of the CP.

We choose the cache hit rate as a measure of QoE, which is a standard measure for cache efficiency. This success rate h is defined as the fraction of the number of requests for the N elements which were found in the cache out of the total number of requests for the N elements; clearly, h is a number between 0 and 1; the higher the success rate, the happier the users; Chances are they get the content they want straight from the cache, without having to wait for the ISP to communicate with the CP to send the requested content back to the ISP. Therefore, this will have a positive impact on the total number of requests arriving at the CP. The success rate h is given by [6]:

$$h = \left(\frac{C}{N}\right)^{1-a} \quad (4)$$

where the popularity of the contents follows a Zipf distribution with parameter a (0 <a <1).

We define the parameter Δ as being proportional to the success rate h: Δ = Fh, with F constant non-negative. Clearly, the lower bound of Δ is zero; in this case, the total number of requests for the contents of the CP, D^C with caching is the same as the total number of requests D without caching.

- The B^C bandwidth, which corresponds to the number of cases where the request of an element of the CP has not been served by the cache, is given by:

$$B^C = B(1 - h) \quad (5)$$

These cases correspond to the cache failure rate.

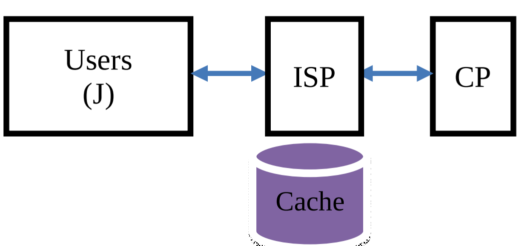

Fig. 2 : scenario of one ISP and one CP with cache at the ISP

Once all of these considerations are done, the utility functions of the ISP and CP can be rewritten as follows:
Usefulness of the CP:

$$U_{CP}^C = (1 + \Delta)DP - O \quad (6)$$

Usefulness of ISP :

$$U_{ISP}^C = \sum_{j=1}^{J} \pi_j - sC - B(1-h)b. \quad (7)$$

By calculating the difference between utilities with caching and utilities without caching, we get:

$$U_{CP}^C - U_{CP} = \Delta DP \quad (8)$$
$$U_{ISP}^C - U_{ISP} = -sC + hBb \quad (9)$$

It is obvious that the deployment of the cache will always result in a positive externality for the income of the CP, since its profit will increase (in the worst case, it will remain stable). While the cache deployment is beneficial to the ISP if and only if the hBb backhaul bandwidth savings are greater than the sC cache cost.

The question we'll answer is whether sharing the cost of cache deployment and the profit generated by caching between the ISP and the CP can be beneficial for both players.

To do this, we model the interaction between the ISP and the CP as a coalition game in which the two actors cooperate to share the investment related to the deployment of the cache and to share the benefit produced by this cache.

The quantity to be shared is:

$$\Phi = (U_{CP}^C - U_{CP}) + (U_{ISP}^C - U_{ISP}) = \Delta DP - sC + hBb \quad (10)$$

The motivation for adopting this model is to ensure alignment of ISP and CP interest in deploying a cache. Knowing that, if the ISP is the only one to invest for the deployment of the cache in its network, we have shown previously that when the cost of the cache is higher than that of the backhaul bandwidth, the ISP has no motivation to deploy this cache. The question, then, is whether CP's involvement in the cache deployment investment will expand the number of instances where the ISP is ready to cache deployment.

Note that the amount Φ corresponding to the additional cost / benefit due to the caching for the ISP and the CP will be the same, either when the ISP pays for the deployment of the cache, or when the ISP and the CP share the cost. / benefit of the cache (or even when the CP offers the cache to the ISP network for free - this is the case with Google nownadays). The difference with our model is how to divide this additional cost / benefit.

To decide how Φ should be shared between the CP and the ISP, we use a well-known solution concept from coalition game theory, the Shapley value formula. This distribution scheme, defined by L. Shapley [4], is an interesting solution in coalition games for its equity. It is the unique distribution satisfying the following axioms: efficiency (i.e., the total surplus is allocated), symmetry (i.e., players with the same contribution in the coalition are paid fairly), dummy (that is, players who have not contributed, the coalition considered is not paid), and additivity (if a game consists of two sub-games, the players receive the sum of their shares in the two sub-parts). Consequently, each actor receives a share of profit proportional to his contribution to the network and to the added value that he brings to the global value chain.

Let Φ_{CP} be the quantity the CP receives and Φ_{ISP} the quantity the ISP receives after applying Shapley's value to the quantity Φ. So :

$$\Phi_{CP} = \frac{1}{2}(\Delta DP - sC + hBb) \quad (11)$$
$$\Phi_{ISP} = \frac{1}{2}(\Delta DP - sC + hBb) \quad (12)$$

The utility functions after applying the Shapley value are:

$$U_{CP}^{C} = DP - O + \Phi_{CP} = DP - O + \frac{1}{2}(\Delta DP - sC + hBb)$$
$$U_{CP}^{C} = \left(DP + \frac{1}{2}(\Delta DP + hBb)\right) - \left(\frac{1}{2}sC + O\right)$$
$$U_{ISP}^{C} = \sum_{j=1}^{J}\pi_j - Bb + \Phi_{ISP}$$
$$= \sum_{j=1}^{J}\pi_j - Bb + \frac{1}{2}(\Delta DP - sC + hBb)$$
$$U_{ISP}^{C} = \left(\sum_{j=1}^{J}\pi_j + \frac{1}{2}(\Delta DP + hBb)\right) - \left(Bb + \frac{1}{2}sC\right) \quad (13)$$

These utility functions each have two components: an investment component and a profit component.
The problem therefore comes down to calculating the optimal caching policy, that is, the optimal choice of the cache size C which maximizes the utility functions of the ISP and the CP.
To do this, let's rewrite the utility functions by introducing the cache hit rate:

$$U_{CP}^{C} = DP - O + \frac{1}{2}\left(\mathrm{F}\left(\frac{C}{N}\right)^{1-a} DP - sC + \left(\frac{C}{N}\right)^{1-a} Bb\right) \quad (14)$$
$$U_{ISP}^{C} = \sum_{j=1}^{J}\pi_j - Bb + \frac{1}{2}\left(\mathrm{F}\left(\frac{C}{N}\right)^{1-a} DP - sC + \left(\frac{C}{N}\right)^{1-a} Bb\right)$$

By performing the first derivatives of these utility functions, we obtain the same expression:

$$U_{CP}^{C}{}' = \frac{1-a}{2N}\left(\frac{C}{N}\right)^{-a}(\mathrm{F}DP + Bb) - \frac{1}{2}s \quad (15)$$
$$U_{CP}^{C}{}' = 0 \Rightarrow C^{\circ} = \sqrt[a]{\frac{(1-a)(FDP + Bb)}{sN^{1-a}}}$$

Then, $U_{CP}^{C}{}'$ is positive in (0, C°) and negative in (C°, N). We distinguish two cases:

a. If $C^{\circ}$is greater than N, then the cache size C^* which maximizes U_{CP}^{C} is N.

b. If C° s less than N, then C^* is equal to C°.

By combining the cases we get this:

$$C^* = min\left\{N\ ,\ \sqrt[a]{\frac{(1-a)(FDP + Bb)}{sN^{1-a}}}\right\} \quad (16)$$

Note that the fact that utilities are maximized for the same cache size implies that it does not matter who controls the size of the cache (the CP or the ISP).
Considering C^*, we rewrite the utilities of CP and ISP as follows:

$$U_{CP}^{C} = \left(DP + \frac{1}{2}\left(\mathrm{F}\left(\frac{C^*}{N}\right)^{1-a} DP + \left(\frac{C^*}{N}\right)^{1-a} Bb\right)\right) - \left(\frac{1}{2}sC^* + O\right) \quad (17)$$
$$U_{ISP}^{C} = \left(\sum_{j=1}^{J}\pi_j + \frac{1}{2}\left(\mathrm{F}\left(\frac{C^*}{N}\right)^{1-a} DP + \left(\frac{C^*}{N}\right)^{1-a} Bb\right)\right) - \left(Bb + \frac{1}{2}sC^*\right) \quad (18)$$

With these expressions we have:

i. The investment made by the CP for the deployment of the cache:

$$Inves_{CP} = \left(\frac{1}{2}sC^* + O\right) \quad (19)$$

- The investment made by the ISP for the deployment of the cache:

$$Inves_{ISP} = \left(Bb + \frac{1}{2}sC^*\right) \quad (20)$$

(22)

- The profit obtained by the CP:

$$Gain_{CP} = \left(DP + \frac{1}{2}\left(\mathrm{F}\left(\frac{C^*}{N}\right)^{1-a} DP + \left(\frac{C^*}{N}\right)^{1-a} Bb\right)\right) - \left(\frac{1}{2}sC^* + O\right) \quad (21)$$

- The profit obtained by the ISP:

$$Gain_{ISP} = \left(\sum_{j=1}^{J}\pi_j + \frac{1}{2}\left(\mathrm{F}\left(\frac{C^*}{N}\right)^{1-a} DP + \left(\frac{C^*}{N}\right)^{1-a} Bb\right)\right) - \left(Bb + \frac{1}{2}sC^*\right) \quad (22)$$

b) **Case of one ISP and several CPs**

We now look at the more general case (see Fig. 3), where there is a single ISP and single trading partners (PCs) that provide additional content to ISP users. This model is generalized as it is for several ISPs, provided that users do not change ISPs.
In the case where there is no caching, we redefine the utility functions using a notation similar to the baseline scenario: For each CP_i, the utility U_i is equal to:

$$U_i = D_i P_i - O_i \qquad (23)$$

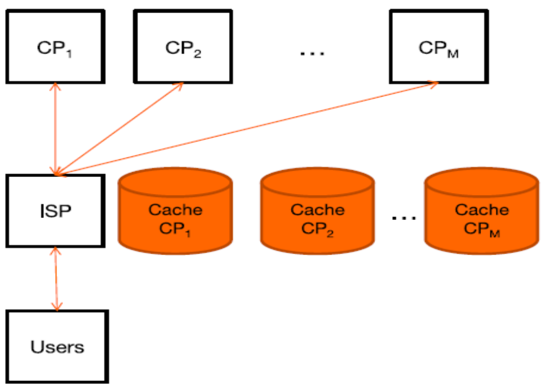

Fig. 3 : scenario of one ISP and several CPs with caches at the ISP

For the ISP, the only difference is that the total backhaul bandwidth B is the sum of the backhaul bandwidth B_i required for the content demand of each CP_i:

$$U_{ISP} = \sum_{j=1}^{J} \pi_j - Bb \ , \qquad B = \sum_{i=1}^{M} B_i$$

We are looking at scenarios where the ISP deploys a cache per CP; we do not consider the case where a cache is shared between different CPs, as this is not supported due to technical restrictions and security (cryptography) considerations. We then distinguish two cases:
When the contents of the PCs do not overlap (for example, the first PC offers sporting events, the second PC offers movies, the third PC offers music, etc.), the basic model is generalized as is; Since the caches are independent, we should just apply the basic model for each cache to find out if the ISP and CP have the motivation to deploy the cache and, if so, how they should share the cost / profit of the cache and what is the optimal caching policy.
When the contents of the PCs overlap. In this case, there is a coupling between the caches; This means that in addition to the coalition game between each CP_i and the ISP, there is a non-cooperative game among the CPs.
It is the latter that will be the subject of our study.
First, we redefine the total demand after caching D_i^C to be equal to:

$$D_i^C = (1 + \Delta_i) D_i \qquad (24)$$

As regards the parameter Δ_i, it is assumed, as previously, that it increases linearly with the success rate of the cache h_i. In addition, we assume that it decreases linearly with the sum of the success rates of all other CPs; this is due to the fact that the caches of other CPs create a negative externality at the request of the CP_i. Therefore, we get this:

$$\Delta_i = F h_i - f \sum_{j \neq i} h_j \qquad (25)$$

$$F \geq (M-1) f \geq 0 \ \ and \ \ 0 \leq f \leq \frac{1}{M-1}$$

The global positive constants F and f are set to ensure that: (i) the parameter Δ_i is not less than -1, since the total demand D_i^C cannot be negative, (ii) D_i^C will be at least equal to D_i, if all the caches have the same success rate, (i.e. the request with caching will be at least equal to the request without caching). We then define the new necessary backhaul bandwidth B_i^C :

$$B_i^C = (1 + \Theta_i) B_i (1 - h_i) \qquad (26)$$

With

$$\Theta_i = -f \sum_{j \neq i} h_j$$

The parameter Θ_i reflects the fact that the backhaul bandwidth B_i ^ C is reduced linearly with the sum of the success rates of all the other caches. Since B_i^C is a non-negative quantity, the smallest possible value of Θ_i is -1, which is ensured by the domain of the global constant f.
Therefore, the utility functions after caching are:
We consider the cost / profit sharing model between ISP and CP.
There is then a coalition game between the ISP and each CP_i in order to share the cost / benefit due to the deployment of the cache.
Let Φ_i be the quantity to be shared:

$$\Phi_i = U_i^C - U_i + U_{ISP}^C - U_{ISP}$$
$$= \Delta_i D_i P_i - sC_i - B_i b(-h_i - \Theta_i h_i + \Theta_i) \qquad (27)$$

Applying Shaplay's theorem, we have the following Shaplay values for CP_i and ISP:

$$\Phi_{CP} = \frac{1}{2}[(\Delta_i + \Theta_i) D_i P_i - sC_i - B_i b(-h_i - \Theta_i h_i)] \qquad (28)$$

$$\Phi_{ISP} = \frac{1}{2}[(\Delta_i - \Theta_i) D_i P_i - sC_i - B_i b(-h_i - \Theta_i h_i + 2\Theta_i)] \qquad (29)$$

The CPs compete with each other to determine the optimal cache size needed to store their content at the ISP.
Non-cooperative play between PCs is defined as follows:

i. The players are the M CP;
ii. The strategy of each player i is the choice of the cache size $C_i \ \epsilon \ [0, N_i]$;
iii. The utility function of each player is given by:

$$U_i = D_i P_i - O_i + \frac{1}{2}[(\Delta_i + \Theta_i) D_i P_i - sC_i - B_i b(-h_i - \Theta_i h_i)] \qquad (30)$$

A powerful solution concept in uncooperative game theory is pure Nash equilibrium (NE) [5] which predicts game outcomes that are stable.

A pure NE corresponds to a stable state of a game in the sense that no player is encouraged to unilaterally change his own strategy.

Using the Debreu-Glicksberg-Fan theorem [5], we show that this game admits a Nash equilibrium.

Debreu-Glicksberg-Fan theorem: Let G be a game in normal form, where, for each player i: (i) The strategy set S_i is compact and convex. (ii) The utility function $U_i(s_i, s_{-i})$ is continuous in s_{-i}. (iii) The utility function $U_i(s_i, s_{-i})$ is continuous and (quasi) concave in s_i. Then, the set G admits a pure NE.

We will show that these three properties are verified in our game:

First, the set of strategies is the closed interval $[0, N_i]$, which is compact and convex.

Next, we rewrite the utility function Ui using the success rate formula:

$$h = \left(\frac{C}{N}\right)^{1-a}$$

$$U_i = D_iP_i - O_i + \frac{1}{2}[(\Delta_i + \Theta_i)D_iP_i - sC_i - B_ib(-h_i - \Theta_i h_i)]$$

$$= D_iP_i - O_i + \frac{1}{2}\left[\left(Fh_i - 2 - f\sum_{j\neq i} h_j\right)D_iP_i - sC_i - B_ib\left(-h_i + f\sum_{j\neq i} h_j\, h_i\right)\right]$$

$$= D_iP_i - O_i - f\sum_{j\neq i}\left(\frac{C_j}{N_j}\right)^{1-a} D_iP_i - \frac{1}{2}sC_i + \frac{1}{2}\left(FD_iP_i + B_ib - f\sum_{j\neq i}\left(\frac{C_j}{N_j}\right)^{1-a} B_ib\right)\frac{1}{N_i^{1-a}}(1-a)C_i^{-a} \quad (31)$$

Clearly, U_i is continuous in C_i, as well as in C_{-i}.

As for the third condition, since U_i is twice differentiable in C_i, it is concave if and only if its second derivative U_i'' is non-positive.

$$U_i' = -\frac{1}{2}s + \frac{1}{2}\left(FD_iP_i + B_ib - f\sum_{j\neq i}\left(\frac{C_j}{N_j}\right)^{1-a} B_ib\right)\frac{1}{N_i^{1-a}}(1-a)C_i^{-a}$$

$$U_i'' = \frac{1}{2}\left(FD_iP_i + B_ib - f\sum_{j\neq i}\left(\frac{C_j}{N_j}\right)^{1-a} B_ib\right)\frac{1}{N_i^{1-a}}(1-a)(-a)C_i^{-a-1}$$

as

$$f\sum_{j\neq i}\left(\frac{C_j}{N_j}\right)^{1-a} \leq \frac{1}{M-1}(M-1) = 1$$

It turns out that all the terms of the product are negative, in addition -a is negative, so U_i'' is always non-positive.

We propose a best response dynamic scheme [5], where each CP_i iteratively updates its cache size C_i (strategy) in order to maximize its utility function U_i. Although in general such a scheme cannot converge to a NE, in concave sets that admit a unique NE it is guaranteed to converge to the NE.

The size of the cache at time t + 1 can be calculated using an iterative scheme by taking into consideration the strategies of all the other CPs at time t and is given by the following formula:

$$C_i(t+1) = max\left\{N_i, \sqrt[a]{\frac{(1-a)K_i(t)}{sN_i^{1-a}}}\right\} \quad (32)$$

$$K_i(t) = FD_iP_i + B_ib - f\sum_{j\neq i}\left(\frac{C_j(t)}{N_j}\right)^{1-a} B_ib$$

This iterative scheme is obtained by taking the first derivative of the utility function Ui and setting it equal to zero in order to calculate the local maximum points; in our case, there is a single maximum point. As usual, a best response dynamics scheme requires an exchange of messages between actors to decide on their new strategies. In our case, each CP_i needs to know the sum of the success rates of all the other CPs to update its strategy and the ISP could provide this information. Note that CPs do not need to know the exact success rate of each CP, they are sufficient to know their sum.

3. SIMULATION AND COMMENTS

We observe here the evolution of the gains and investments made by the ISP and the CP engaged in the caching strategy.

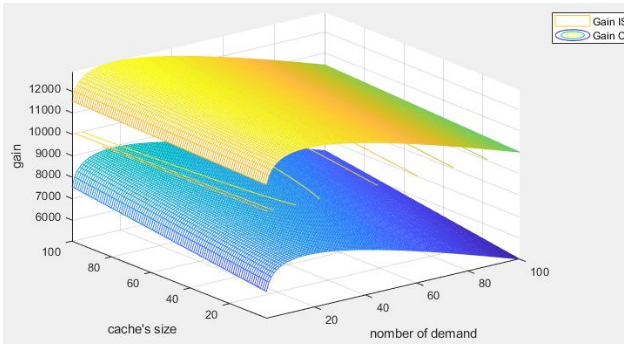

Figure 4 *: evolution of players' earnings*

The shapes of the gain curves of the two players are similar.

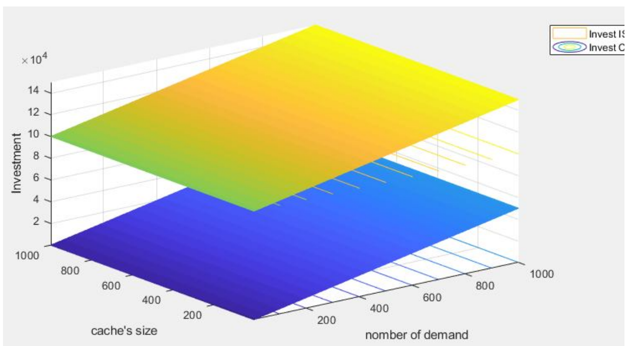

Figure 5 : evolution of stakeholder investments

We also see here a similarity in the shape of the investment curves of the two players.

4. Conclusion

From this study, it emerges that cooperation between internet service providers and content providers is necessary to deploy cache servers in the networks of internet service providers. this cooperation makes it possible not only to share the investments, but also the benefits. It then encourages internet service providers to accept the deployment of caches in their networks.

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