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Caching games between Content Providers and Internet Service Providers[☆]

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ABSTRACT

We consider a scenario where an Internet Service Provider (ISP) serves users that choose digital content among M Content Providers (CP). In the status quo, these users pay both access fees to the ISP and content fees to each chosen CP; however, neither the ISP nor the CPs share their profit. We revisit this model by introducing a different business model where the ISP and the CP may have motivation to collaborate in the framework of caching. The key idea is that the ISP deploys a cache for a CP provided that they share both the deployment cost and the additional profit that arises due to caching. Under the prism of coalitional games, our contributions include the application of the Shapley value for a fair splitting of the profit, the stability analysis of the coalition and the derivation of closed-form formulas for the optimal caching policy.

Our model captures not only the case of non-overlapping contents among the CPs, but also the more challenging case of overlapping contents; for the latter case, a non-cooperative game among the CPs is introduced and analyzed to capture the negative externality on the demand of a particular CP when caches for other CPs are deployed.

1. Introduction and contributions

The Internet ecosystem is classically described as an interconnection of Autonomous Systems (ASs) [1], exchanging traffic through peering (free of charge) contracts or customer–provider contracts. The ASs have been classified by [2] into five categories: Large Transit Providers, Small Transit Providers, Access/Hosting Providers, Enterprise Customers, and Content Providers. From an AS perspective, the ASs that are involved in a customer–provider link with a transit Internet Service Provider (ISP) pay this latter for the traffic volume that flows through this link.

From an end user perspective, the current Internet pricing model involves two customer–provider relationships: (i) Access fees, where end users pay a fee to access ISPs for the connectivity services, based, in general, on flat offers. (ii) Content pricing, where end users pay directly or indirectly (e.g., via advertisement) to the Content Providers (CP).

An alternative Internet economic model has been proposed by Ma et al. in [3]; the idea being that end users pay for end-to-end services provided by a set of ISPs, and ISPs collectively share the revenue generated from these customers based

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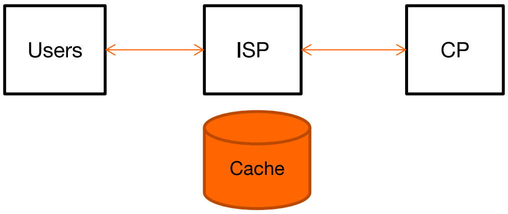

Fig. 1. Baseline scenario: the case of 1 CP.

on a profit distribution mechanism. Notions from the coalitional game theory [4] have been used for designing the profit distribution mechanism to ensure fairness and efficiency properties.

Towards this direction, the goal of our work is to analyze a business model where the ISP and the CPs collaborate by sharing the cache cost/profit deployment. We use coalitional game theory to model the interactions between them and we make the following contributions:

For the case that there is a unique CP: (i) We use the Shapley value [4] to propose a fair splitting of the – due to caching – profit between the CP and the ISP. (ii) We compute the Nash Bargaining Solution [4] that has also appealing properties, showing that it coincides with the Shapley value for our model. (iii) We analyze the stability of the Shapley value, showing under which conditions it belongs to the core [4] of the game. (iv) We compute the optimal caching policy that maximizes the revenue of both the ISP and the CP. Our simulations show that there is a significant increase in the profit of the ISP and the CP with respect to the case that there is no cache deployment.

For the case that there are multiple CPs: (i) We compute the Shapley value. (ii) We analyze the non-cooperative game [5] that arises due to the competition among the CPs. (iii) We prove that this game admits always a Nash Equilibrium (NE). (iv) We derive a necessary and sufficient condition for the uniqueness of the NE. (v) We propose a best-response dynamics scheme that converges fast to the NE.

2. Baseline model: The case of one Content Provider

2.1. Preliminaries

We consider a scenario with one ISP that serves J users and one CP that offers additional content (movies, sports, etc.) to these users (see Fig. 1); let N be the number of items that the CP sells and let P be the price per item. Each user j pays both access fees to the ISP and content fees to the CP. Note that we do not take into consideration indirect costs (e.g., from ads shown as part of search results).

Then, we compute the profit for the ISP and the CP, expressed as a utility function that captures the difference between the income minus the expenses. The utility for the CP, denoted by U_{CP}, is the difference between the content fees (*i.e.*, the total demand D for the N items from the J users multiplied by the price per item P) that the users of the ISP pay to him[1] minus his operational expenses, denoted by O. Therefore, we get that: $U_{\mathrm{CP}} = DP - O$.

On the other hand, the utility of the ISP, denoted by U_{ISP}, is the difference between the sum of the access fee π_j that each user j pays to the ISP minus the product of the backhaul bandwidth B needed for serving the demand D for the CP contents multiplied by the unit backhaul bandwidth cost b. Therefore, we get that: $U_{\mathrm{ISP}} = \sum_{j=1}^{J} \pi_j - Bb$.

2.2. The impact of caching

In this section, we examine the impact of caching on the utility functions of the ISP and the CP. In our context, the adoption of caching incurs three changes in the model:

- There is a cache deployment cost; for a cache of size C and with a unit cache cost s, this is equal to sC.
- The total demand D for the N items of the CP will change; this is due to the fact that the demand is based on the perceiving Quality-of-Experience (QoE) of the users and when a cache for the CP is deployed by the ISP, this has a direct impact on the users' QoE.
- The backhaul bandwidth B needed will change due to caching, since some of the requests for the contents of the CP could be served directly by the cache.

In order to quantify the above factors, we examine the case that the ISP deploys a cache of size C, storing proactively the C most popular items out of the N items of the CP. Let D^C be the new demand for the contents of the CP; the superscript C

2 We use the pronoun "he" when we refer to the ISP/CP, implying the owner of the ISP/CP.

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