Information-Centric Networking Cache Memory Allocation: A Network Economics Approach

Aisha B Rahman*‡, Panagiotis Charatsaris†‡, Eirini Eleni Tsiropoulou*, and Symeon Papavassiliou†
{arahman3@unm.edu, pancharatsaris@netmode.ntua.gr, eirini@unm.edu, papavass@mail.ntua.gr}
* Dept. of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM, USA
† School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece

***Abstract*—Information Centric Networking (ICN) paradigm exploits the in-network caching capacity to support the process of fast and efficient content distribution. In addition to the algorithmic and implementation challenges associated with the decision-making of content placement, the sustainability of content caching frameworks heavily depends on the design of appropriate network economics models to define and support the interactions among the involved players. In order to treat this need, in this paper, considering multiple Content Providers (CPs) while exploiting the in-network caching model, we particularly examine the joint problem of maximizing the CPs profit and their market penetration in terms of attracting a large portion of customers. The problem is formulated as a non-cooperative game among the CPs and the existence and uniqueness of a Pure Nash Equilibrium (PNE) are proven. The performance evaluation of the proposed network economics-based approach is achieved via modeling and simulation, while its superiority against other alternatives is demonstrated.**

***Index Terms*—Information Centric Networking, Networks Economics, Game Theory, Content Providers.**

I. Introduction

The mobile data traffic is increasing sharply in recent years, especially given the plethora of wireless streaming applications of on-demand videos. Content caching can effectively decrease the quantity of redundant data transmissions by exploiting *edge caching*, where the content is cached on edge devices, access points (APs), edge servers, and gNBs (next-generation nodes B), and *in-network caching* by following the Information Centric Networking (ICN) paradigm and caching content on the users' nearby routers [1]. However, in order for content caching to become a sustainable solution, appropriate network economics models need to be in place that jointly benefit the ICN provider, the Content Providers (CPs), such as YouTube, Netflix, Amazon Video, Hulu, just to name a few, and improve the users' Quality of Experience (QoE). In this paper, aligned with the latter vision, a network economics approach is introduced enabling the CPs to autonomously decide their optimal cache memory purchase from the ICN provider, in order to maximize their profit, penetrate the market in terms of served users, and provide improved content delivery services to the users.

‡ The authors had equal contribution.

The research of Dr. Tsiropoulou was partially supported by the NSF Awards #2219617 and #2319994.

A. Related Work

Several recent research works have studied network economics problems in content caching to support its sustainable deployment [2]. A Stackelberg game-theoretic approach is introduced in [3] to enable the CPs to decide the optimal caching memory that they should purchase from APs in order to satisfy the users' Quality of Service (QoS) constraints. An actor-critic reinforcement learning approach is proposed in [4] in order to support the CPs to learn the optimal number of virtual machines that they should lease from the edge servers towards minimizing their cost given the content demand of their customers. The problem of optimizing the content caching and network benefits, i.e., social welfare, is studied in [5] by formulating a profit split problem between the CPs and the Internet Service Providers (ISPs) and solving it based on a Stackelberg game-theoretic approach, concluding to a win-win solution for both parties.

Towards bridging the gap between the ISPs and the CPs, which have competing interests in terms of making profit, the principles of Contract Theory have been extensively adopted to design viable network economics models [6]. In [7], the ISP acts as the employer offering contracts to the CPs, i.e., employees, based on their content caching needs. The goal is to maximize the ISP's profit, while guaranteeing that the CPs have sufficient incentives, i.e., individual rationality and incentive compatibility, to participate in the content caching market. A contract-theoretic model between the CP (employer) and the users (employees) is discussed in [8], where the CP aims at maximizing its profit, considering the content demand of the users, as well as their imposed constraints in terms of content's age of information and content delivery latency. A different perspective in the field of content caching is analyzed in [9], where the caching nodes are considered selfish and the authors introduce a selfish caching game to maximize the overall system's social welfare, while determining the optimal amount of cache memory leased at each caching node.

Developing network economics models to support the in-network caching, following the ICN paradigm, has recently attracted the interest of the research community [10]. A time-based caching pricing model is introduced in [11] where the ICN provider charges the CPs for a certain amount of time that they lease cache memory in the ICN provider's available routers. A detailed comparison between the package and traffic billing models is performed in [12], where the ICN provides a cap-based or a usage-based pricing to the CPs based on their requested traffic. The proposed study concludes to the observation that the package billing model is more in line with the needs of the ICN provider, the CPs, and the users in terms of each one optimizing their profit and service goals.

B. Contributions and Outline

While there has been extensive literature on the design of pricing models for edge caching, the design and analysis of holistic network economics frameworks considering multiple competing CPs in an ICN environment remains largely unexplored. This paper aims exactly at filling this gap, and to the best of our knowledge, it is the first effort in the literature to examine the joint problem of maximizing the CPs profit and their market penetration in terms of attracting a large portion of customers, while serving multiple areas following the ICN paradigm. Our primary contributions are summarized as follows.

1) A novel ICN cache memory allocation model is introduced, where multiple CPs serve a number of areas of interest via exploiting the in-network caching model and proactively caching content in the ICN provider's routers following the recently commercially released sponsored data plan. Based on the latter one, the users consume the CPs' proactively cached content by paying a small usage-based fee. The users' personalized payoff is discussed considering their personal evaluation of receiving the requested content, the CP's service guarantees and corresponding service cost.
2) A non-cooperative game is formulated among the CPs to determine the optimal cache memory leased by each CP at each serving area towards jointly maximizing its own profit and market penetration, i.e., attracting a large portion of customers. The existence and uniqueness of a Pure Nash Equilibrium (PNE) are proven.
3) A detailed evaluation is performed demonstrating that the CPs who invest more in terms of securing a minimum leased cache memory, become more dominant in the market in terms of both profit making and attracting a large portion of customers. A detailed scalability analysis and a comparative evaluation of the proposed approach to other network economics based alternatives is performed demonstrating the superiority of the proposed model in terms of CPs' profit and users' experienced service.

The rest of the paper is organized as follows: Section II introduces the ICN cache memory model. The joint problem of CPs' profit and market penetration maximization is formulated as a non-cooperative game in Section III, and the existence and uniqueness of the PNE is proven. The performance evaluation of the proposed approach is demonstrated via modeling and simulation in Section IV, while Section V concludes the paper.

II. ICN Cache Memory Allocation Model

An ICN content caching environment is considered consisting of an ICN provider, a set of CPs $\mathcal{C} = \{1, \dots, c, \dots, C\}$, and a set of users $\mathcal{U} = \{1, \dots, u, \dots, U\}$. Each CP can serve several areas of interest, with the set of the latter denoted as $\mathcal{A} = \{1, \dots, a, \dots, A\}$. Each CP has a minimum cache memory demand $\boldsymbol{\delta}_c = [\delta_c^1, \dots, \delta_c^a, \dots, \delta_c^A]$[Bytes] to serve each area and support the sponsored data plan provided to the users. The concept of the sponsored data plan was first introduced by AT&T [13], where the users consume the CPs' proactively cached content for free or they pay a small fee, while a usage-based pricing model is applied for on-demand content that is not already pre-cached. Each CP c leases cache memory d_c^a [Bytes] at each serving area $a \in \mathcal{A}$ from the ICN provider, with $d_c^a \geq \delta_c^a$, in order to serve the users.

Towards capturing the CP's market penetration in terms of attracting customers, we follow the principles of the Tullock Contest framework [14]. The Tullock Contest framework has been introduced in the Economics Theory as a strategic model to capture the interactions among players with competing interests, as is the case of the CPs regarding the market penetration. Based on the Tullock Contest framework, the CPs invest their personal resources, i.e., payment to lease cache memory from the ICN provider, in order to win a prize, i.e., contest, which is translated to their market penetration and the corresponding number of customers that they attract. The probability of a CP c winning the contest is defined by the Contest Success Function (CSF) $\mathcal{P}_c^a$ that depends on the CP's invested effort to win the contest via leasing cache memory d_c^a and collecting a corresponding payment from the users P_c^a. Following the design principles of the CSF under the Tullock Contest framework, we define the CSF as follows:

$$\mathcal{P}_c^a(d_c^a, P_c^a) = \frac{MS_c^a(d_c^a, P_c^a)}{\sum\limits_{\forall c' \in \mathcal{C}} MS_{c'}^a(d_{c'}^a, P_{c'}^a)} \tag{1}$$

where $P_c^a(d_c^a)$ is the payment that the CP c collects from the users for delivering the content d_c^a in area a. Aligned with the usage-based pricing, the price can be defined as $P_c^a(d_c^a) = d_c^a$. Also, the market share function $MS_c^a(d_c^a, P_c^a)$ captures each CP's c potential to attract users, considering its penetration in the market (first term of Eq. 2) and its total pricing of its services (second term of Eq. 2). Therefore, the market share function can be defined as follows:

$$MS_c^a(d_c^a, P_c^a) = f(d_c^a) \cdot g(P_c^a) \tag{2}$$

where $f(d_c^a)$ is a continuous, concave, non-decreasing function with respect to the leased cache memory d_c^a by CP c in an area a, e.g., $f(d_c^a) = \sqrt{d_c^a}$, and $g(P_c^a)$ is a continuous, concave, decreasing function with respect to the users' payment P_c^a for the provided services, e.g., $g(P_c^a) = -(P_c^a)^2 + P_c^a + \delta_c^a$. It is evident that if a CP leases a higher amount of cache memory ($f(\cdot)$ function) and provides a lower cost/users' payment ($g(\cdot)$ function), while guaranteeing the services under the sponsored data plan, has the potential to achieve a higher market penetration.

Based on the previous analysis and considering that a set $\mathcal{U}^a \subseteq \mathcal{U}$ of users reside in each serving area a, the expected number of users being served by CP c in all the serving areas is given as follows:

$$\mathbb{E}[\mathcal{U}_c^a] = \sum_{\forall a \in \mathcal{A}} |\mathcal{U}^a| \mathcal{P}_c^a(d_c^a, P_c^a) = \sum_{\forall a \in \mathcal{A}} |\mathcal{U}^a| \cdot \frac{MS_c^a(d_c^a, P_c^a)}{\sum\limits_{\forall c' \in \mathcal{C}} MS_{c'}^a(d_{c'}^a, P_{c'}^a)} \quad (3)$$

Thus, the CP's c profit from leasing the cache memory and serving the users in all the areas a is given as follows,

$$\Pi_c(\mathbf{d}) = \sum_{\forall a \in \mathcal{A}} P_c^a |\mathcal{U}^a| \mathcal{P}_c^a(d_c^a, P_c^a) - \sum_{\forall a \in \mathcal{A}} k^a \cdot d_c^a \quad (4)$$

where $\mathbf{d} = [\mathbf{d}_1, \dots, \mathbf{d}_c, \dots, \mathbf{d}_C]$, $\mathbf{d}_c = [d_c^1, \dots, d_c^a, \dots, d_c^A]$ and k^a $[\frac{\$}{Bytes}]$ denotes the unit cost of leasing the cache memory.

Focusing on the users' characteristics, each user receives a personalized payoff $e_{u,c}^a$ based on the content d_c^a that is provided in area a (first term of Eq. 5), while paying a service cost $P_c(d_c^a)$ based on the amount of content that is provided in area a (second term in Eq. 5). Also, the user's payoff decreases as the number of users served by CP c in area a increases (denominator of Eq. 5), as the network conditions can deteriorate due to network congestion. Thus, the user's payoff from the content caching and delivery process is formulated as follows:

$$U_{u,c}^a(|\mathcal{U}_c^a|, d_c^a) = \frac{e_{u,c}^a(d_c^a) - P_c^a(d_c^a)}{\mathbb{E}[\mathcal{U}_c^a]} \quad (5)$$

where $e_{u,c}(d_c^a)$ is a continuous, increasing, concave function with respect to the available content d_c^a, e.g., $e_{u,c}^a(d_c^a) = w_{u,c}^a\sqrt{d_c^a + 1}$, where $w_{u,c}^a \in \mathbb{R}^+$ captures the user's personal weight of the experienced content delivery service and a larger value of $w_{u,c}^a$ shows that the user values more the consumed content.

III. Content Providers Profit Maximization

The goal of each CP is to maximize its profit by leasing cache memory d_c^a at each serving area a from the ICN provider, and optimize its market penetration to exploit the revenue from the users' payment. Thus, the corresponding optimization problem for each CP is formulated as follows,

$$\max_{\mathbf{d}_c \in D_c} \Pi_c(\mathbf{d}_c, \mathbf{d}_{-c}) \quad (6)$$

where D_c is the strategy set of each CP c in terms of leasing cache memory, with $D_c = D_c^1 \times \dots \times D_c^a \times \dots D_c^A$, and $D_c^a = [\delta_c^a, +\infty)$ is the cache memory needs in each area a. Also, $\mathbf{d}_{-c} = [\mathbf{d}_1, \dots, \mathbf{d}_{c-1}, \mathbf{d}_{c+1}, \dots, \mathbf{d}_C]$ is the strategy vector of leasing cache memory of all other CPs except for CP c.

The optimization problem in Eq. 6 can be addressed as a non-cooperative game $G = [\mathcal{C}, \{D_c\}_{\forall c \in \mathcal{C}}, \{\Pi_c\}_{\forall c \in \mathcal{C}}]$ among the C CPs, where D_c denotes the strategy set of each CP, and Π_c is its profit, i.e., payoff function (Eq. 4). Our goal is to show the existence and uniqueness of a Pure Nash Equilibrium (PNE) for the non-cooperative game G.

Definition 1: **(Pure Nash Equilibrium):** A strategy vector $\mathbf{d}^* = [\mathbf{d}_1^*, \dots, \mathbf{d}_c^*, \dots, \mathbf{d}_C^*]$ is a PNE of the non-cooperative game $G = [\mathcal{C}, \{D_c\}_{\forall c \in \mathcal{C}}, \{\Pi_c\}_{\forall c \in \mathcal{C}}]$ if for every CP c the following condition holds true:

$$\Pi_c(\mathbf{d}_c^*, \mathbf{d}_{-c}^*) \geq \Pi_c(\mathbf{d}_c, \mathbf{d}_{-c}^*), \quad \forall \mathbf{d}_c \in D_c$$

In the following analysis, we show the existence and uniqueness of PNE for the non-cooperative game G to enable each CP c to determine the optimal cache memory d_c^{a*} leased at each area a from the ICN provider.

Theorem 1: (**Existence of PNE**) A PNE $\mathbf{d}^* = [\mathbf{d}_1^*, \dots, \mathbf{d}_c^*, \dots, \mathbf{d}_C^*]$ exists for the non-cooperative game $G = [\mathcal{C}, \{D_c\}_{\forall c \in \mathcal{C}}, \{\Pi_c\}_{\forall c \in \mathcal{C}}]$.

Proof: Towards proving the existence of a PNE, we need to show that the non-cooperative game G is a concave n-person game [15]. Thus, the necessary and sufficient conditions are: (i) the strategy set D_c is a convex, closed, and bounded set; and (ii) the payoff function $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ is continuous in $\mathbf{d}$ and concave in $\mathbf{d}_c, \forall c \in \mathcal{C}$. Based on the definition of the CPs' strategy set D_c, the first condition holds true, and based on Eq. 4, the CP's profit function $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ is continuous in $\mathbf{d}$. To prove the concavity of $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ in $\mathbf{d}_c$, we have: $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c}) = \sum_{\forall a \in \mathcal{A}} \frac{d_c^a |\mathcal{U}^a| \sqrt{d_c^a}(-{d_c^a}^2 + d_c^a + \delta_c^a)}{A} - \sum_{\forall a \in \mathcal{A}} k^a d_c^a$, where $A = \sum_{\forall c' \in C} MS_{c'}^a(d_{c'}^a, P_{c'}^a)$, and for simplicity in the notation, we set $\Phi(d_c^a) = \sqrt{d_c^a}$, and $\gamma(d_c^a) = -{d_c^a}^2 + d_c^a + \delta_c^a$. We have: $\Phi'(d_c^a) = \frac{1}{2}{d_c^a}^{-\frac{1}{2}} > 0$, $\Phi''(d_c^a) = -\frac{1}{4}{d_c^a}^{-\frac{3}{2}} < 0$, $\gamma'(d_c^a) = -2d_c^a + 1 < 0$ for $d_c^a > \frac{1}{2}$, and $\gamma''(d_c^a) = -2 < 0$, and $A > 0$ for all practical scenarios and values of $\delta_c^a, \forall c \in \mathcal{C}$ and $a \in \mathcal{A}$. Thus, we have:

$$\frac{\partial \Pi_c}{\partial d_c^a} = \frac{|\mathcal{U}^a|}{A}[\Phi(d_c^a) \cdot \gamma(d_c^a) + d_c^a \Phi'(d_c^a) \cdot \gamma(d_c^a) + d_c^a \Phi(d_c^a) \cdot \gamma'(d_c^a)] - k^a$$

and

$$\frac{A}{|\mathcal{U}^a|} \cdot \frac{\partial^2 \Pi_c}{\partial {d_c^a}^2} = \Phi'(d_c^a)\gamma(d_c^a) + \Phi(d_c^a)\gamma'(d_c^a) + \Phi'(d_c^a)\gamma(d_c^a) + d_c^a \Phi''(d_c^a)\gamma(d_c^a) + d_c^a \Phi'(d_c^a)\gamma'(d_c^a) + \Phi(d_c^a)\gamma'(d_c^a) + d_c^a \Phi'(d_c^a)\gamma'(d_c^a) + d_c^a \Phi(d_c^a)\gamma''(d_c^a)$$

We have: $d_c^a \Phi''(d_c^a)\gamma(d_c^a) < 0$, $d_c^a \Phi'(d_c^a)\gamma'(d_c^a) < 0$, and $d_c^a \Phi(d_c^a)\gamma''(d_c^a) < 0$. We examine the sign of $\Phi'(d_c^a)\gamma(d_c^a) + \Phi(d_c^a)\gamma'(d_c^a)$ as follows: $\Phi'(d_c^a)\gamma(d_c^a) + \Phi(d_c^a)\gamma'(d_c^a) = \frac{1}{2}{d_c^a}^{-\frac{1}{2}} \cdot (-{d_c^a}^2 + d_c^a + \delta_c^a) + {d_c^a}^{\frac{1}{2}}(-2d_c^a + 1) < 0 \Leftrightarrow -5{d_c^a}^2 + 3d_c^a + \delta_c^a < 0$ for the realistic range of values for d_c^a and δ_c^a. Thus, the $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ function is concave with respect to $d_c^a, \forall c \in \mathcal{C}, \forall a \in \mathcal{A}$, and the Hessian matrix of $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ is negative definite, as all its eigenvalues are negative and we have $\frac{\partial^2 \Pi_c}{\partial d_c^a \partial d_{c'}^a} = \frac{\partial^2 \Pi_c}{\partial d_{c'}^a \partial d_c^a} = \frac{1}{2} A^{-2} \frac{\partial A}{\partial d_{c'}^a} |\mathcal{U}^a| [\Phi(d_c^a)\gamma(d_c^a) + d_c^a \Phi'(d_c^a)\gamma(d_c^a) + d_c^a \Phi(d_c^a)\gamma'(d_c^a)] - k^a$, thus, the Hessian matrix of $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ is also a Hermetian matrix. Therefore, the payoff function $\Pi_c(\mathbf{d_c}, \mathbf{d}_{-c})$ is concave in $\mathbf{d_c}$, and the non-cooperative game G is a concave n-person game and a PNE exists. ■

Our next step is to show that the PNE is also unique.

Definition 2: **(Diagonal Strict Concavity):** Consider the non-cooperative game G with the pseudogradient $\lambda(\mathbf{d}, \mathbf{r})$:

$$\lambda(\mathbf{d}, \mathbf{r}) = \begin{pmatrix} r_1 \nabla_1 \Pi_1(\mathbf{d}) \\ \vdots \\ r_C \nabla_C \Pi_C(\mathbf{d}) \end{pmatrix}$$

where $\mathbf{d} = [\mathbf{d}_1, \dots, \mathbf{d}_c, \dots, \mathbf{d}_C]$ and $\mathbf{r} = [r_1, \dots, r_c, \dots, r_C]$. The function $\sigma(\mathbf{d}, \mathbf{r}) = \sum_{c=1}^{C} r_c \Pi_c(\mathbf{d}), \mathbf{r} \geq \mathbf{0}$ is called diagonal strict concave for $\mathbf{d} \in \mathbb{R}$ and fixed $\mathbf{r} \geq \mathbf{0}$ if for every $\mathbf{d}^0, \mathbf{d}^1 \in \mathbb{R}$, we have:

$$(\mathbf{d}^1 - \mathbf{d}^0)' \lambda(\mathbf{d}^0, \mathbf{r}) + (\mathbf{d}^0 - \mathbf{d}^1)' \lambda(\mathbf{d}^1, \mathbf{r}) > 0.$$

Theorem 2: The weighted non-negative sum of the CPs' profit $\sigma(\mathbf{d}, \mathbf{r}) = \sum_{c=1}^{C} r_c \Pi_c(\mathbf{d})$ is diagonally strictly concave function for some $\bar{\mathbf{r}} > \mathbf{0}$.

Proof: Towards proving this Theorem, we can equivalently prove that the symmetric matrix $\Lambda(\mathbf{d}, \bar{\mathbf{r}}) + \Lambda'(\mathbf{d}, \bar{\mathbf{r}})$ is negative definite for $\mathbf{d} \in \mathbb{R}$, where $\Lambda(\mathbf{d}, \bar{\mathbf{r}})$ is the Jacobian matrix of $\lambda(\mathbf{d}, \bar{\mathbf{r}})$, based on Theorem 6 in [15]. Based on the Lemma in [16], in order to show that $\Lambda(\mathbf{d}, \bar{\mathbf{r}}) + \Lambda'(\mathbf{d}, \bar{\mathbf{r}})$ is negative definite, we need to prove the following conditions: (C1) $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ strictly concave in $\mathbf{d}_c$, (C2) $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ convex in $\mathbf{d}_{-c}$, and (C3) there is some $\bar{\mathbf{r}} > 0$, such that $\sigma(\mathbf{d}, \bar{\mathbf{r}})$ is concave in $\mathbf{d}$. The condition (C1) holds true based on the proof in Theorem 1. Towards proving (C2), we determine the eigenvalues of the Hessian Hermitian matrix of $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c})$ with respect to the strategies of the rest of CPs $c', \forall c' \in C \setminus \{c\}$, as follows. For notation convenience, we set $B = d_c^a |\mathcal{U}^a| MS_c^a(d_c^a, P_c^a)$ and $\Gamma = \sum_{\forall a \in \mathcal{A}} k^a d_c^a$, thus, $\Pi_c(\mathbf{d}_c, \mathbf{d}_{-c}) = \sum_{\forall a \in \mathcal{A}} \frac{B}{\sum_{\forall c' \in C} \sqrt{d_{c'}^a}(-{d_{c'}^a}^2 + d_{c'}^a + \delta_{c'}^a)} - \Gamma$ and we have:

$$\frac{1}{B}\frac{\partial \Pi_c}{\partial d_{c'}^a} = -\frac{\frac{1}{2}{d_{c'}^a}^{-\frac{1}{2}}(-{d_{c'}^a}^2 + d_{c'}^a + \delta_{c'}^a) + \sqrt{d_{c'}^a}(-2d_{c'}^a + 1)}{d_{c'}^a(-{d_{c'}^a}^2 + d_{c'}^a + \delta_{c'}^a)^2}$$

$$\text{and} \qquad \frac{1}{B}\frac{\partial^2 \Pi_c}{\partial {d_{c'}^a}^2} = \frac{-3{\delta_{c'}^a}^2 + 2\delta_{c'}^a d_{c'}^a (3d_{c'}^a - 5)}{4{d_{c'}^a}^{\frac{5}{2}}[(d_{c'}^a - 1)d_{c'}^a - \delta_{c'}^a]^3} + \frac{{d_{c'}^a}^2(-35{d_{c'}^a}^2 + 42d_{c'}^a - 15)}{4{d_{c'}^a}^{\frac{5}{2}}[(d_{c'}^a - 1)d_{c'}^a - \delta_{c'}^a]^3} \geq 0 In$$

$$\Leftrightarrow 0 < d_{c'}^a < \frac{1}{2}(\sqrt{2\delta_{c'}^a + 1} + 1)$$

which holds true for the realistic values of $d_{c'}^a, \delta_{c'}^a > 0$. Thus, condition (C2) holds true. Also, for $\bar{\mathbf{r}}_c = \frac{1}{d_c^a}, \forall c \in \mathcal{C}, \forall a \in \mathcal{A}$, we check that $\sigma(\mathbf{d}, \bar{\mathbf{r}})$ is concave in $\mathbf{d}$ and the condition (C3) is satisfied. Thus, the non-negative sum of the CP's profit $\sigma(\mathbf{d}, \bar{\mathbf{r}}) = \sum_{c=1}^{C} r_c \Pi_c(\mathbf{d})$ is diagonally strictly concave function. ■

Theorem 3: (**Uniqueness of PNE**) The non-cooperative game $G = [\mathcal{C}, \{D_c\}_{\forall c \in \mathcal{C}}, \{\Pi_c\}_{\forall c \in \mathcal{C}}]$ has a unique Nash Equilibrium.

Proof: Based on Theorem 2 in [15], if $\sigma(\mathbf{d}, \bar{\mathbf{r}})$ is diagonally strictly concave function for some $\bar{\mathbf{r}} > 0$, then the equilibrium point $\mathbf{d}^* = [\mathbf{d}_1^*, \dots, \mathbf{d}_c^*, \dots, \mathbf{d}_C^*]$ is a unique PNE of the non-cooperative game $G = [\mathcal{C}, \{D_c\}_{\forall c \in \mathcal{C}}, \{\Pi_c\}_{\forall c \in \mathcal{C}}]$. ■

Towards determining the unique PNE of the non-cooperative game G, a best response dynamics algorithm can be adopted and deployed [17].

IV. Numerical Evaluation

In this section, a detailed numerical evaluation is performed in order to demonstrate the pure operational characteristics, scalability, and superiority of the proposed network economics approach in terms of maximizing the CPs' profit and enabling them to penetrate the market while improving the content delivery services to the users. Specifically, Section IV-A presents the pure operation and performance of the proposed approach both from the CPs' and the users' perspective, while Section IV-B introduces a scalability analysis in order to demonstrate the efficiency and robustness of the proposed framework. Finally, Section IV-C presents a comparative evaluation of the proposed framework against other alternative approaches that have been introduced in the state-of-the-art in order to demonstrate its superiority in terms of CPs' profit maximization, ICN's experienced income, and users' achieved utility. For the purposes of our evaluation we have considered a setting consisting of five CPs and ten different service areas. In particular, throughout the rest of the analysis, unless otherwise explicitly stated, the following parameters have been used: $A = 10$, $|\mathcal{U}^a| = [94, 88, 82, 76, 70, 64, 58, 52, 46, 40]$, $\delta_1^a \in [1.15, 0.65]$ TiB, $\delta_2^a \in [1.05, 0.55]$ TiB, $\delta_3^a \in [0.95, 0.45]$ TiB, $\delta_4^a \in [0.85, 0.35]$ TiB, $\delta_5^a \in [0.75, 0.25]$ TiB, $k^a = [2.6, 3.02, 3.44, 3.86, 4.28, 4.7, 5.12, 5.54, 5.96, 6.38]$, $w_{u,c}^a \in [2, 30]$.

A. Pure Operation and Performance

Figs. 1a-1c present the leased cache memory, the contest success rate, and the expected number of users of the five CPs as a function of the areas ID. Also, Figs. 1d-1f present the CPs' cost/ICN income (second term of Eq.4), the CPs' revenue (first term of Eq.4), and the CPs' profit (Eq.4) as a function of the CP's ID. It is noted that for the simulation purposes, we have considered that the higher the area's ID, the smaller the number of users residing in it, while the higher the CP's ID, the lower the minimum cache memory demand δ_c^a that they lease. Accordingly, the lower the CP's ID, the higher the summation of the minimum cache memory demand that characterizes each CP.

The results reveal that the CPs which are more willing to lease cache memory, i.e., lower CP's ID being characterized by a higher minimum cache memory demand $\boldsymbol{\delta}_c$, conclude in purchasing a larger amount of cache memory at each area (Fig. 1a), thus, achieving a higher contest success rate (Fig.

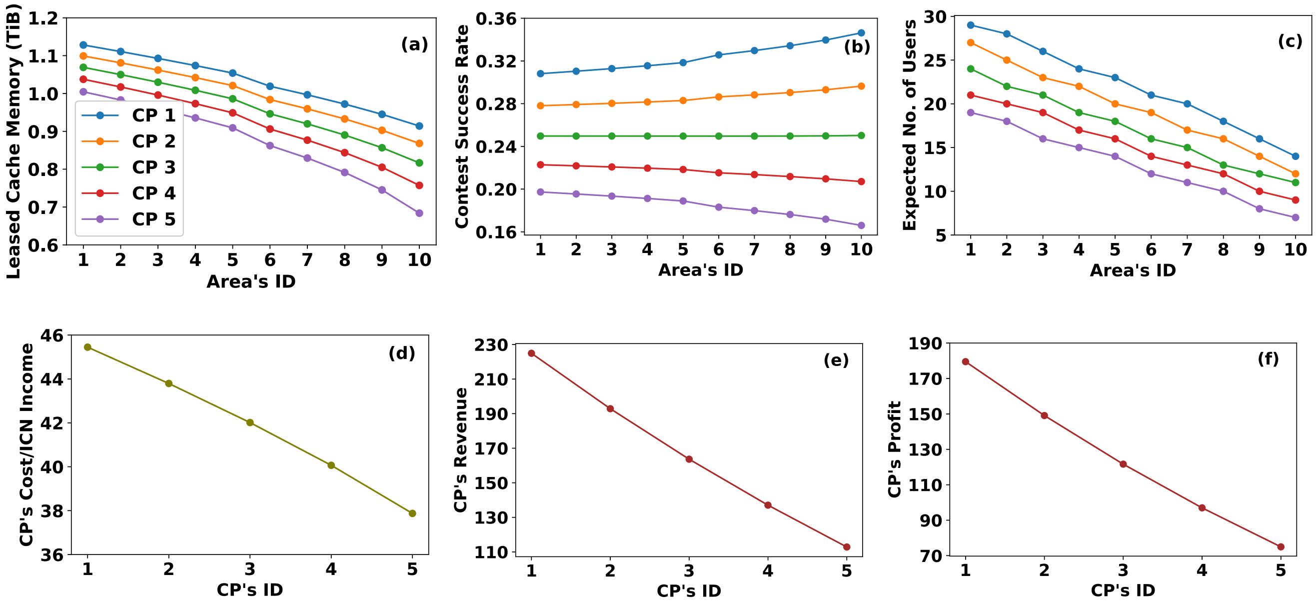

Fig. 1: Performance evaluation of the proposed framework from the CPs' perspective.

1b), and attracting a larger number of users to serve (Fig. 1c). Also, the areas that are characterized by a lower demand in terms of cache memory, i.e., higher ID areas, drive the CPs to lease a lower amount of cache memory. Focusing on the contest success rate presented in Fig. 1b, the results illustrate that the CPs with higher ID, which are also characterized by a lower summation of the minimum cache memory demand as explained before, i.e., $\sum_{\forall a \in \mathcal{A}} \delta_c^a$, are becoming less successful in the contest competition of attracting users to be served by them. Thus, the lower ID CPs become more successful in terms of attracting a larger portion of the users in the corresponding areas. Focusing on Figs. 1d-1f, the results show that the higher the CPs ID, the lower the amount of leased cache memory per serving area (Fig. 1a), thus, the corresponding CPs experience a lower cost (Fig. 1d), but also a lower revenue (Fig. 1e). Consequently, the CPs with higher ID achieve an overall lower profit by serving the corresponding users (Fig. 1f).

Fig. 2a presents the users' evaluation, i.e., $e_{u,c}(d_c^a)$, for five indicative users which are characterized by a higher intensity of wants [18] for a higher area ID, i.e., $w_{u,c}^a$, being served by one representative CP, e.g., CP 1, while a higher user ID corresponds also to a higher intensity of wants. Also, Fig. 2b presents the users' average utility, as it is quantified in Eq. 5, being served by a corresponding CP as a function of the area's ID. The results reveal that the higher the user's intensity of wants, the higher the experienced evaluation of the delivered cached content (Fig. 2a), as the users value more the delivered service by the CP provider. The results demonstrate that the CPs, which serve a smaller number of users, i.e., CPs with higher ID, are capable of delivering a better service to the users, resulting in a higher average utility for the latter ones (Fig. 2b). Furthermore, the service

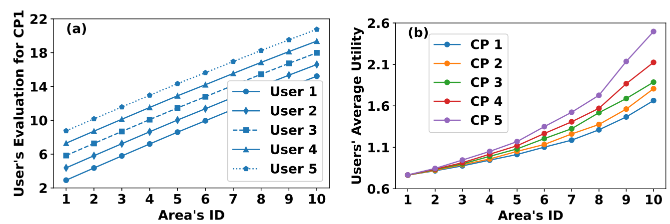

Fig. 2: Performance evaluation of the proposed framework from the users' perspective.

areas which are characterized by a lower number of users (i.e., higher ID areas), deliver a better service, as the users experience lower congestion.

B. Scalability Analysis

Figs. 3a-3b present the CPs' profit and the users' average utility, respectively, as a function of the percentage increase of the number of users per area. The results show that as the number of users per area increases, the CPs' profit also increases, while the users' average utility decreases due to the increased congestion while delivering the cached content to the users. Specifically, an 80% increase of the number of users per area approximately results in 100% increase of the CPs' profit and in a corresponding average decrease of the users average utility by 17%. These results verify that overall the proposed approach presents a robust content delivery service.

C. Comparative Evaluation

In this section, a comparative evaluation of the proposed network economics approach realizing the information-centric networking cache memory allocation is performed against alternative strategies that have been introduced in the state-of-the-art in order to quantify its benefits and tradeoffs. Specifically, the proposed cache memory allocation framework

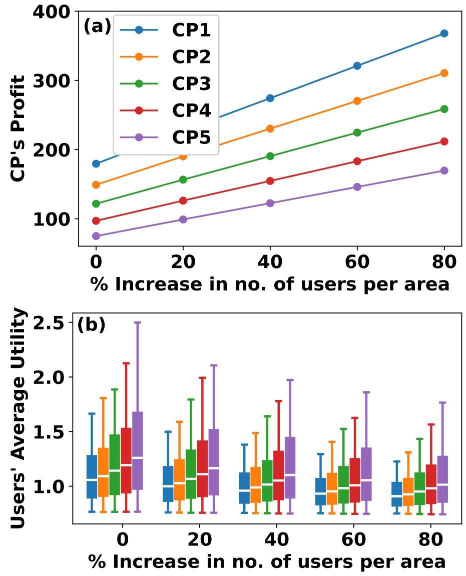

Fig. 3: Scalability analysis.

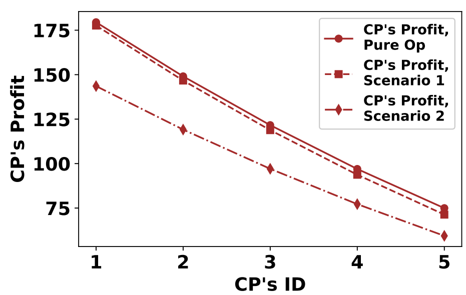

Fig. 4: Comparative evaluation.

is compared to two different scenarios: (i) Scenario 1: each CP aims at maximizing its profit while considering the same minimum cache memory demand at each area regardless of the number of users residing in it; (ii) Scenario 2: each CP tries to maximize its market penetration, i.e., the number of users that it serves. In particular, Fig. 4 presents the CPs' profit as a function of the CP's ID. The results demonstrate that the proposed cache memory allocation framework benefits all the CPs in terms of experiencing an increased profit compared to the rest of the evaluated scenarios. In contrast, Scenario 2 that aims at maximizing only the CP's market penetration, results in the worst CP's profit due to the myopic perception of the content caching market. Also, the CPs profit is worse under Scenario 1 due to the fact that in this case the CPs do not consider the content demand that characterizes each serving area.

V. Conclusion

In this paper, the problem of jointly maximizing the CPs' profit and their market penetration while serving multiple areas following the ICN paradigm is studied. Specifically, we consider that the CPs follow the sponsored data plan in order to deliver content to the users and they exploit the in-network caching model. A non-cooperative game is formulated among the CPs towards determining their optimal cache memory leased at each serving area in order to jointly maximize their profit and market penetration. The existence and uniqueness of a Pure Nash Equilibrium are shown, while a detailed performance evaluation of the proposed framework is conducted in order to demonstrate its operational characteristic and benefits.

Our current and future work contains the extension of the proposed model by considering a multi-ICN provider environment, where an additional degree of freedom is introduced, as the CPs may also select the specific ICN provider from which to lease their necessary cache memory.

References

[1] Q. Wang, S. Guo, J. Liu, C. Pan, and L. Yang, "Motishare: Incentive mechanisms for content providers in heterogeneous time-varying edge content market," *IEEE Transactions on Services Computing*, vol. 16, no. 1, pp. 452–465, 2023.

[2] S. He and W. Wang, "Price-driven economic cache content nash bargaining game in wireless multimedia resource allocation," in *2019 28th International Conference on Computer Communication and Networks (ICCCN)*, 2019, pp. 1–8.

[3] C. Jiang, L. Gao, T. Wang, J. Luo, and F. Hou, "On economic viability of mobile edge caching," in *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*, 2020, pp. 1–6.

[4] T. Hou, G. Feng, S. Qin, and W. Jiang, "Proactive content caching by exploiting transfer learning for mobile edge computing," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, 2017, pp. 1–6.

[5] C. Fang, C. Liu, Z. Wang, Y. Sun, W. Ni, P. Li, and S. Guo, "Cache-assisted content delivery in wireless networks: A new game theoretic model," *IEEE Systems Journal*, vol. 15, no. 2, pp. 2653–2664, 2021.

[6] T. Liu, J. Li, F. Shu, H. Guan, Y. Wu, and Z. Han, "Incentive mechanism design for two-layer wireless edge caching networks using contract theory," *IEEE Transactions on Services Computing*, vol. 14, no. 5, pp. 1426–1438, 2021.

[7] J. Li, S. Chu, F. Shu, J. Wu, and D. N. K. Jayakody, "Contract-based small-cell caching for data disseminations in ultra-dense cellular networks," *IEEE Transactions on Mobile Computing*, vol. 18, no. 5, pp. 1042–1053, 2019.

[8] X. Zhou, W. Wang, N. U. Hassan, C. Yuen, and D. Niyato, "Towards small aoi and low latency via operator content platform: A contract theory-based pricing," *IEEE Transactions on Communications*, vol. 70, no. 1, pp. 366–378, 2022.

[9] Q. Ma, E. Yeh, and J. Huang, "Selfish caching games on directed graphs," *IEEE/ACM Transactions on Networking*, vol. 29, no. 2, pp. 709–722, 2021.

[10] A. B. Rahman, P. Charatsaris, M. S. Siraj, and E. E. Tsiropoulou, "Symbiotic content caching in next-generation information-centric networking," *IEEE International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)*, pp. 1–8, 2023.

[11] C. Zhang, "Time-to-live based caching mechanism with nonlinear pricing for information-centric networks," in *2021 IEEE 6th International Conference on Smart Cloud (SmartCloud)*, 2021, pp. 57–60.

[12] Q. Zheng, J. Lin, W. Yan, Z. Xu, Q. Shi, and X. Tan, "Research on icn caching and pricing strategies under the package billing model," in *GLOBECOM 2022 - 2022 IEEE Global Communications Conference*, 2022, pp. 4667–4672.

[13] "At&t Sponsored Plan, 2014," Available online at https://www.att.com/.

[14] G. Tullock, *The rent-seeking society*. Selected Works of Gordon Tullo, 2005, vol. 5.

[15] J. B. Rosen, "Existence and uniqueness of equilibrium points for concave n-person games," *Econometrica: Journal of the Econometric Society*, pp. 520–534, 1965.

[16] J. C. GOODMAN, "For concave n-person games," *Econometrica*, vol. 48, no. 1, 1980.

[17] E. E. Tsiropoulou, G. K. Katsinis, and S. Papavassiliou, "Utility-based power control via convex pricing for the uplink in cdma wireless networks," in *European Wireless Conference*, 2010, pp. 200–206.

[18] L. Price, "Henry rogers seager. introduction to economics," *The Economic Journal*, vol. 14, no. 55, pp. 423–427, 1904.