

Symbiotic Content Caching in Next-Generation Information-Centric Networking

Aisha B Rahman*, Panagiotis Charatsaris[†], Md Sadman Siraj*, Eirini Eleni Tsiropoulou*

* 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—The continuous growth of mobile data traffic with strict time requirements calls for the development of sustainable edge content caching solutions. This becomes more prominent in the setting of Information-Centric Networking (ICN) architectures, where different ICNs are leasing caching slices to the available content providers (CPs), who in turn offer their services to the users. In this paper, we introduce a novel symbiotic content caching framework that provides the necessary economic benefits to the ICNs and the CPs to mutualistically collaborate among each other. The corresponding mutualistic interactions among the ICNs and CPs are studied under the prism of two different market-based models, namely the competitive market and oligopoly market models. A game-theoretic approach is followed in order to determine the optimal leasing prices of the ICNs' content caching slices and the CPs' optimal amount of leased caching memory from the ICNs. The performance evaluation of the proposed new symbiotic content caching paradigm is achieved via modeling and simulation, while the benefits and drawbacks of the competitive and oligopoly market modeling approaches are revealed and discussed.

Index Terms—Content Caching, Information-Centric Networking, Game Theory, Stackelberg Games.

I. INTRODUCTION

The mobile data traffic continues to rise sharply, with annual traffic of almost 1 zettabyte by the end of 2022, while approximately 79% of the world's mobile traffic is video [1]. Online video streaming Content Providers (CPs), such as Hulu, Amazon Video, Netflix, YouTube, just to name a few, have dramatically contributed to the rapid growth of the data traffic. Towards delivering the timely content delivery to the users, the concept of edge caching has been proposed, where the CPs cache content on edge devices closer to the users. The edge caching has additional multiple benefits such as lowering bandwidth consumption, shortening the delay in obtaining the content, alleviating backbone network burden and meeting explosive traffic demands [2]. However, in order for edge caching to become a sustainable solution, the Internet Service Providers (ISPs) and the CPs should both benefit in terms of profit from such a solution [3]. The ISPs are responsible for routing the traffic and delivering the content to the users. Also, in the case of Information-Centric Networking (ICN), the ISPs

support in-network caching by caching content on the users' nearby routers. Thus, the CPs should buy cache slices from the ISPs in order for the content of the former ones to be cached on the routers of the latter ones. On the other hand, the users are charged by the CPs based on the content that they consume, thus, the CPs should purchase the appropriate services and/or infrastructure from the ISPs to guarantee fast content delivery to the users. In this paper, aiming at developing a sustainable network economics model among the Content Providers (CPs) and the Information-Centric Networking providers (ICNs), we introduce a novel symbiotic content caching framework inspired by the evolution of biological ecosystems, along with a next-generation ICN paradigm to support the rapid increase of video mobile data traffic.

A. Related Work

The problem of developing network economics models to support the sustainable deployment of edge caching has attracted the interest of the research community in the last years [4]. In [5], the authors introduce a three-stage Stackelberg game in order to jointly maximize the profits of the ISPs and CPs, and the utilities of the users. The Stackelberg Equilibrium is determined based on a sub-gradient iterative algorithm that monotonically converges to the equilibrium. A similar theoretical approach is followed in [6], where the ISPs, CPs, Access Providers (APs), and the users are involved in the three-stage Stackelberg game. In this case the Stackelberg Equilibrium jointly determines the cache space purchased by the CPs, the users' cache fee, the backbone, and wireless access services prices by the ISPs and APs, respectively. A two-stage Stackelberg game is formulated in [7] among the ISPs and the CPs in order to achieve maximum network benefits and optimal content caching, respectively. The concept of cache leasing is discussed in [8], where the CPs lease memory space from the ISPs in order to cache their content. A corresponding distributed optimization problem for each CP is formulated and solved aiming at maximizing each CP's traffic offloading with minimum leasing cost.

Edge caching can support a great variety of communication and services paradigms, such as vehicular networks, and device-to-device communications. A cooperative edge caching framework is introduced in [9] in order to enable the vehicle to fetch location-based and popular content from

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multiple caching servers. The cooperation takes place among the caching servers in order to determine the optimal content proportions and placing location, accounting for the corresponding service cost. A similar approach is proposed in [10] to determine the optimal content caching in roadside units (RSUs) considering the vehicles' content access pattern, velocity, and road traffic density while assuming that the RSUs cooperate among each other. A market-based edge caching approach in vehicular networks is designed in [11], where the Public Transportation Companies (PTCs) lease on-board cache storage in their mobile vehicles to the CPs. A Stackelberg game is formulated among the PTCs (leaders) and the CPs (followers) in order to determine the optimal leasing price and cache storage space, respectively, towards optimizing the performance of the caching storage. Focusing on the problems of edge caching in D2D communication systems, a pricing scheme is presented in [12], where seller and buyer devices co-exist. An optimal buying, caching, and reselling game-theoretic model is introduced to determine the optimal amount of allocated cached content bought by the seller devices from the CPs and the corresponding optimal reselling price to the buyer devices. A similar approach is introduced in [13], where the seller devices have the option to become sellers or not, following an evolutionary game-theoretic approach.

With the advent of the Information-Centric Networking (ICN), content caching became the main criterion in the design of networking architectures. In the ICN, the first time requested content is retrieved by the origin server of the CP, while any subsequent request of the same content is retrieved from the caches implemented in the intermediate routers. Thus, the ICN, as it is currently designed, is location-independent and the content can be cached and retrieved anywhere in the network. In [14], an auction-based content caching approach is discussed, where the ISPs lease caching space in their routers to the CPs, while the latter ones can dynamically replace the content cached in their purchased caching spaces based on the users' requests. The direct interaction among the ICN providers (ICNs), who cache content in their routers, and users is studied in [15]. The authors formulate an optimization problem to determine the ICNs' optimal pricing and the users' optimal content consumption strategies. A game-theoretic approach is presented in [16] to jointly determine the caching and pricing strategies of the ICNs, while considering different levels of content popularity. However, these research works consider that all the ICNs have similar characteristics in terms of serving geographical areas and the content is dynamically cached in the routers without exploiting in advance any potential users' interests in content per area [17].

B. Contributions & Outline

While pricing-based mechanisms enabling mobile edge caching have been thoroughly studied in the literature, their integration into the information-centric networking paradigm is still in its infancy. Also, the ICN paradigm is currently location-agnostic in terms of delivering content to the end-

users, which still suffer from high delays even if the content is dynamically cached in the on-path routers. Motivated by these research gaps, in this article, we introduce a novel next-generation information-centric networking architecture to facilitate the sponsored content paradigm of the content providers, along with a new symbiotic content caching framework that provides the necessary economic benefits to the ICNs and the CPs to mutualistically collaborate among each other. Specifically, the main contributions of this paper are summarized as follows.

- 1) A novel next-generation information-centric networking architecture is introduced consisting of the access, regional, and core ICN providers (ICNs). The ICNs are leasing caching slices [18] to the content providers (CPs), such as Netflix, Hulu, YouTube, etc., who can in advance cache content to the ICNs routers to avoid the delay of the first-control requests by the users. The CPs and the ICNs adopt the concept of sponsored data plan, first introduced by AT&T [19], where the CPs pay the ICNs for the caching slices of the cached content consumed by the users, while the users consume the CPs cached content for free or they pay a small fee. This novel ICN architecture is mutually beneficial for all the involved entities, i.e., ICNs, CPs, and users, as the CPs pay for only their real caching needs, caching in advance the content in the ICNs' routers, the ICNs collect profit from leasing their caching slices, the users consume for free (or with a small fee) the CPs' cached content, and the network's traffic congestion is ultimately reduced.
- 2) Considering the novel ICN architecture, a bio-inspired symbiotic content caching model is introduced to capture the mutualistic interactions among the ICNs and CPs under the prism of two market-based models. Initially, a competitive market model is studied among the access, regional, and core ICNs, who fully compete with each other to set the caching slices' prices, while satisfying the content caching needs of the CPs. The competitive market model is formulated as a non-cooperative game among the ICNs and the existence of a Pure Nash Equilibrium is shown. The Nash Equilibrium (NE) determines the ICNs' optimal caching slices' prices in the competitive caching market.
- 3) Then, an oligopoly market model is analyzed, where the core ICN acts as the leader making an initial decision of the optimal caching slices price in order to maximize its profit. The core ICN acts as the leader due to its higher infrastructure availability in terms of caching routers and its larger coverage area in the network. The regional and access ICNs act as followers competing with each other to get a larger portion of the content caching market. This interaction among the ICNs at the different levels is captured by a Stackelberg game and the Stackelberg Equilibrium is analytically determined, thus, calculating the ICNs' optimal caching slices' prices.
- 4) A detailed simulation-based evaluation is performed

to jointly demonstrate the benefits of the novel next-generation ICN architecture and the new symbiotic content caching paradigm. Also, a comparative evaluation of the competitive and oligopoly market modeling, highlights the drawbacks and benefits of the two types of markets under different use case scenarios.

The rest of the paper is organized as follows. Section II describes the next-generation ICN architecture and the symbiotic content caching paradigm, along with the symbionts' characteristics. Section III presents the competitive market model among the various ICNs, while Section IV introduces the oligopoly market model among the core ICN and the regional and access ICNs. Section V provides the performance evaluation of the proposed symbiotic content caching framework under both models, while Section VI concludes the paper.

II. NEXT-GENERATION INFORMATION-CENTRIC NETWORKING

A. A Symbiotic Modeling

Inspired by the evolution of the biological ecosystems, we study the interactions among the ICNs and the CPs under the prism of the mutualistic symbiosis. Symbiosis, in principle, is defined as the close relationship and prolonged association between two or more different species, which are called symbionts. The symbionts engaging in the mutualistic symbiosis benefit from their interaction, and they cannot survive the one without the other. In a mutualistic symbiotic relationship, the involved symbionts can exchange resources, services, or a combination of them, among them. Through this exchange of services and/or resources, both parties benefit, survive, and evolve. A typical example of mutualistic symbiosis is the relationship between the Egyptian plover bird and the Nile crocodile. The Nile crocodile offers tiny bits of meat, i.e., a resource from between its teeth to the Egyptian plover bird, by simply opening its mouth and waiting for the bird. On the other hand, the Egyptian plover bird, provides a service to the Nile crocodile, by flossing its teeth. Both species cannot survive the one without the other, as the bird cannot get meat food in any other way and the crocodile cannot clean its teeth in any other way, and the crocodile needs healthy teeth in order to capture its prey. Following this bio-inspired analogy, the ICNs, acting as the Nile crocodile, provide the resource of caching slices at their routers to the CPs, in order for the latter ones to cache in advance or on-the-fly their content, and ultimately decrease the latency in delivering the content to the end-users. On the other hand, the CPs provide a service to the ICNs to stay in business. It is evident that the ICNs and the CPs cannot operate the one without the support of the other, thus they engage in a mutualistic symbiotic relationship.

B. System Model

Considering the identified mutualistic symbiotic environment among the ICNs and CPs, we introduce a novel next-generation ICN architecture. Three different types of ICNs are considered, named access, regional, and core ICNs, which

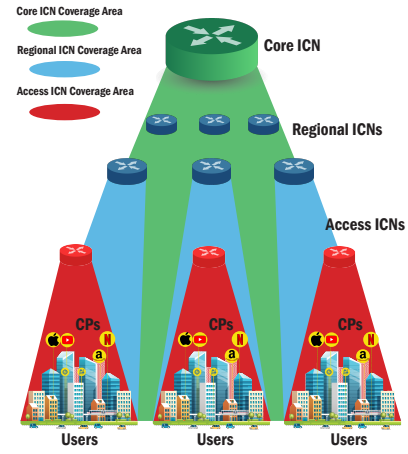


Fig. 1: System Model

are identified based on their coverage area depending on their deployed routers infrastructure, as presented in Fig. 1. The set of ICNs is denoted as $\mathcal{P} = \{A, R, C\}$, i.e., access (A), regional (R), and core (C) ICNs. Also, each ICN provider can support different geographical areas, as shown in Fig. 1. The overall set of areas is denoted as $\mathcal{A} = \{1, \dots, a, \dots, |\mathcal{A}|\}$, where the set of serving areas by each ICN provider is denoted as $\mathcal{A}_A, \mathcal{A}_R, \mathcal{A}_C$, for the access, regional, and core ICNs, respectively. Following the indicative example in Fig. 1, we have: $\mathcal{A}_A = \{3, 5, 7\}$, $\mathcal{A}_R = \{2, \dots, 7\}$, $\mathcal{A}_C = \{1, \dots, 7\}$. Thus, the ICNs create a hierarchical next-generation ICN architecture based on their available routers infrastructure in order to be able to cache the CPs' content following the in-network caching principles and deliver the content to the end-users in an even faster manner, compared to the existing ICN architecture.

The ICNs lease caching slices at their routers to the CPs for a corresponding price related to the cache memory that the CPs request. The ICNs pricing vector is denoted as $\mathbf{P} = [\mathbf{P}_A, \mathbf{P}_R, \mathbf{P}_C] [\frac{\$}{Mbytes}]$, where $\mathbf{P}_A = [P_{A,3}, P_{A,5}, P_{A,7}]$, $\mathbf{P}_R = [P_{R,2}, P_{R,3}, \dots, P_{R,7}]$, and $\mathbf{P}_C = [P_{C,1}, P_{C,2}, \dots, P_{C,7}]$. The ICNs can lease two types of cache memory to the CPs. The exclusively used by an CP cache memory, which act as a safe resource given its non-shared nature, and the dynamically used cache memory, which acts as a Common Pool of Resource (CPR) [20], and the CPs can dynamically access it based on their on-demand content caching needs. The safe cache memory has a fixed high price $P_f [\frac{\$}{Mbytes}]$, which is usually the same among the ICNs, while the CPR cache memory has a variable price $\mathbf{P} = [\mathbf{P}_A, \mathbf{P}_R, \mathbf{P}_C]$ that is shaped dynamically in the network based on the CPs' CPR cache memory demand, and the corresponding availability CPR cache memory by the ICNs [21]. Focusing on the CPs' point of view, the CPs follow the sponsored data plan paradigm, where they provide their content to the users for free or with a small fee, if the users consume content already owned by the CPs. Any other type of content is provided on-demand by the CPs to improve the users' experience. In order for the CPs to improve the

users' experienced Quality of Service (QoS), they strategically cache in-advance content to the ICNs routers following the in-network caching paradigm, in order to decrease the users' experienced latency at the first-attempt accessing the content and for the continuous content delivery. Towards achieving this goal and realizing the sponsored data plan concept, the CPs lease safe caching slices from the ICNs in order to cache in advance their proprietary content based on the statistically analyzed users' preferences per area. The set of CPs is denoted as $\mathcal{I} = \{1, \dots, i, \dots, I\}$, where indicative CPs are Netflix, Hulu, YouTube, etc. Each CP's safe caching slices demand per area a from each ICN provider $p \in \mathcal{P}$ is denoted as $b_{i,p,a}^{safe}[Mbytes]$. Also, the CPs dynamically lease CPR cache memory from the ICNs and the corresponding caching demand of each CP i at each area a from each ICN provider p is denoted as $b_{i,p}^a[Mbytes]$.

In the following analysis, we consider that the ICNs aim at maximizing their profit by leasing safe and CPR caching slices to the CPs, while acting in a rational and selfish manner. Also, the CPs aim at maximizing their experienced caching service utility, while considering the leasing caching slices' cost. Both symbionts, i.e., ICNs and CPs, need to smoothly interact with each other in order to converge to a stable operational equilibrium.

C. Symbionts Characteristics

Each CP aims at maximizing its experienced caching service utility, while dynamically deciding the amount of CPR cache memory that it purchases from the ICNs per each of the serving areas. It is noted that the safe cache memory needs are fixed and non-negotiable for each CP in order to serve the sponsored data plan and satisfy its customers, i.e., end-users. On the other hand, the CP's CPR cache memory demand can dynamically be shaped by the ICNs' announced price. Thus, the corresponding optimization problem for each CP can be formulated as follows:

$$\mathbf{P1:} \quad \max_{b_{i,p}^a} [U_i(\mathbf{b}_i) - \sum_{p \in \mathcal{P}} P_{p,a} \cdot b_{i,p}^a] \quad (1a)$$

$$\text{s.t.} \quad P_{p,a} \geq 0, \quad \forall p \in \mathcal{P}, \forall a \in \mathcal{A} \quad (1b)$$

$$b_{i,p}^a \geq 0, \quad \forall i \in \mathcal{I} \quad (1c)$$

where $P_{p,a}[\frac{\$}{Mbytes}]$ is the price of the CPR cache memory announced by ICN provider $p \in \mathcal{P}$, in area $a \in \mathcal{A}$, and $U_i(\mathbf{P})$ is the CP's pure caching service utility experienced by the CP $i \in \mathcal{I}$, as a function of the purchased CPR cache memory $\mathbf{b}_i$ in each of its serving areas from all the ICNs. The CPs' pure caching service utility function $U_i(\mathbf{b}_i)$ can be defined as a quadratic and strictly concave function, where the CP's CPR cache memory demand is linear, by extending the Singh and Vives model [22] as follows:

$$U_i(\mathbf{b}_i) = \alpha_A b_{i,A}^a + \alpha_R b_{i,R}^a + \alpha_C b_{i,C}^a - \frac{\beta_A b_{i,A}^a{}^2 + \beta_R b_{i,R}^a{}^2}{2} - \frac{\beta_C b_{i,C}^a{}^2 + 2\gamma b_{i,A}^a b_{i,R}^a + 2\epsilon b_{i,A}^a b_{i,C}^a + 2\zeta b_{i,A}^a b_{i,C}^a}{2} \quad (2)$$

where all the coefficients are real numbers and we can determine their values by exploiting the optimization problem's (1a)–(1c) constraints, as explained in the following analysis. The optimization problem (1a)–(1c) can be solved by determining the solution of the following set of linear equations: $\frac{\partial}{\partial b_{i,p}^a} [U_i(\mathbf{b}_i) - \sum_{p \in \mathcal{P}} P_{p,a} b_{i,p}^a] = 0, \forall p \in \mathcal{P} = \{A, R, C\}$. To solve this linear system, we determine the determinants $D_{b_{i,A}^a}$, $D_{b_{i,R}^a}$, $D_{b_{i,C}^a}$, and D , and all of them should be positive in order to find a feasible solution that satisfies Eq. 1c. Thus, based on these derived inequalities we can determine the values of all the coefficients in Eq. 2. Then, the optimal leased CPR cache memory of each CP can be determined as follows by solving the optimization problem (1a)–(1c) at each area $a \in \mathcal{A}$ that the CP serves:

$$b_{i,p}^a(\mathbf{P}) = B_{i,p} - \mu_A^i P_{A,a} + \mu_{A,C}^i P_{C,a} + \mu_{A,R}^i P_{R,a} \quad (3)$$

where $B_{i,p} = \frac{\beta_R \beta_C \alpha_A + \lambda_{R,C}^2 \alpha_A + \lambda_{R,A} \beta_C \alpha_R - \lambda_{C,R} \lambda_{C,A} \alpha_R}{D} + \frac{-\lambda_{R,A} \lambda_{C,R} \alpha_C + \lambda_{C,A} \alpha_C \beta_R}{D}$ with $\lambda_{A,R} = \gamma$, $\lambda_{R,C} = \epsilon$, $\lambda_{A,C} = \zeta$, and $D = -\beta_A(\beta_R \beta_C - \lambda_{R,C}^2) + \lambda_{A,R}(\lambda_{A,R} \beta_C - \lambda_{R,C} \lambda_{A,C}) - \lambda_{A,C}(\lambda_{R,C} \lambda_{A,R} - \beta_R \lambda_{A,C})$ and $\mu_A^i = \frac{\beta_C \beta_R - \lambda_{C,A}^2}{D}$, $\mu_{A,C}^i = \frac{\lambda_{C,R} \lambda_{C,A} - \lambda_{R,A} \beta_C}{D}$, $\mu_{A,R}^i = \frac{\lambda_{R,A} \lambda_{C,R} - \lambda_{C,A} \beta_R}{D}$ and applying the index rotation in the general case.

Based on the above analysis, the CPs' aggregated CPR cache memory demand $D_{p,a}(\mathbf{P})$ from an ICN provider $p, \forall p \in \mathcal{P}$, in each area a can be determined as follows:

$$D_{p,a}(\mathbf{P}) = \sum_{i \in \mathcal{I}_a} b_{i,p}^a \quad (4)$$

$$= B_{p,a} - \mu_A^a P_{A,a} + \mu_{A,C}^a P_{C,a} + \mu_{A,R}^a P_{R,a}$$

where $\mathcal{I}_a$ is the set of CPs serving area a , $B_{p,a}[Mbytes]$ denotes the CPs' CPR cache memory demand in an area a from an ICN provider p , and the coefficient μ_A^a captures the sensitivity of the CPs' CPR cache memory demand to a price change when the CPs are served by the ICN provider A , while the coefficients $\mu_{A,C}^a$ and $\mu_{A,R}^a$ capture the flow of CPs' CPR cache memory demand from the ICNs C and R considering an offered price by them to the CPs, respectively.

Focusing on the ICNs' characteristics, the profit of each ICN provider $p \in \mathcal{P}$, at each area $a \in \mathcal{A}$ that it serves, can be derived as follows:

$$\Pi_{p,a}(P_{p,a}, \mathbf{P}_{-p,a}) = D_{p,a} P_{p,a} + \left(\sum_{i \in \mathcal{I}_a} b_{i,p,a}^{safe} \right) P_f - \sum_{i \in \mathcal{I}_a} b_{i,p,a}^{safe} \cdot d_p \left[B_p^{safe} - \frac{B_{p,a} - D_{p,a}}{\sum_{i \in \mathcal{I}_a} b_{i,p,a}^{safe}} \right] \quad (5)$$

The profit of each ICN provider p consists of the revenue from leasing CPR cache memory to the CPs (first term of Eq. 5), and safe cache memory (second term of Eq. 5) while considering its experienced cost from not satisfying the CPs' safe cache memory request (third term of Eq. 5). Specifically, each CP's minimum safe cache memory request is denoted as $B_p^{safe}[Mbytes]$, considering CPs with similar requests, and the ICNs' discount factor is $d_p\%$ of the price P_f for the safe cache memory. Considering all the areas that each ICN provider serves, its corresponding profit can be derived as follows:

$$\Pi_p(\mathbf{P}_p, \mathbf{P}_{-p}) = \sum_{\forall a \in A_p} \Pi_{p,a}(P_{p,a}, \mathbf{P}_{-p,a}) \quad (6)$$

where $\mathbf{P}_{-p}$ denotes the price vector of all the ICNs except for the ICN provider p .

III. COMPETITIVE MARKET MODEL

The ICNs compete among each other in order to maximize their profit via getting a share of the CPR cache memory demand from the CPs. The ICNs' competition can have different forms, such as a fully competitive market model or an oligopoly market model. In this section, we analyze the scenario where the ICNs participate in a competitive market model to determine the optimal prices of their CPR cache memory in each of their serving areas in order to maximize their profit. Thus, the corresponding optimization for each ICN provider can be formulated as follows:

$$\max_{\{P_{p,a}\} \forall a \in A_p} \Pi_p(\mathbf{P}_p, \mathbf{P}_{-p}) = \sum_{\forall a \in A_p} \Pi_{p,a}(P_{p,a}, \mathbf{P}_{-p,a}) \quad (7a)$$

$$\text{s.t.} \quad P_{p,a} \geq 0, \forall a \in A_p \quad (7b)$$

Given the competitive nature of the ICNs, which act as selfish profit maximizers, their interactions can be captured as a non-cooperative game $G = [\mathcal{P}, \{\mathbb{P}_p\}_{\forall p \in \mathcal{P}}, \{\Pi_p\}_{\forall p \in \mathcal{P}}]$, where $\mathcal{P} = \{A, R, C\}$ is the set of players, i.e., ICNs, $\mathbb{P}_p$ is the price strategy set of the ICN provider p , and Π_p is its payoff function, i.e., its profit, as defined in Eq. 6. Our goal is to show the existence of at least one Nash Equilibrium in order for the overall symbiotic content caching ICN environment to operate in a beneficial manner, i.e., ICNs, CPs, and users.

Definition 1. (Nash Equilibrium - NE): The price vector $\mathbf{P}^* = [\mathbf{P}_A^*, \mathbf{P}_R^*, \mathbf{P}_C^*]$ is a Nash Equilibrium for the non-cooperative game $G = [\mathcal{P}, \{\mathbb{P}_p\}_{\forall p \in \mathcal{P}}, \{\Pi_p\}_{\forall p \in \mathcal{P}}]$, if for every ICN provider $p \in \mathcal{P}$, it holds true that $\Pi_p(\mathbf{P}_p^*, \mathbf{P}_{-p}^*) \geq \Pi_p(\mathbf{P}_p, \mathbf{P}_{-p}^*), \forall \mathbf{P}_p \in \mathbb{P}_p$.

The non-cooperative $G = [\mathcal{P}, \{\mathbb{P}_p\}_{\forall p \in \mathcal{P}}, \{\Pi_p\}_{\forall p \in \mathcal{P}}]$ has a compact and continuous strategy set $\mathbb{P}_p, \forall p \in \mathcal{P}$ and we can easily show that the payoff function $\Pi_p(\mathbf{P}_p, \mathbf{P}_{-p})$ is concave with respect to the ICN providers' strategy. Thus, we can conclude that at least one Nash Equilibrium exists for the non-cooperative game G . Towards determining the Nash Equilibrium, the concept of the best response function

represents the best response strategy selected by an ICN provider, given the strategies of the rest of the ICNs, and it can be defined as follows:

$$\mathcal{B}_p(\mathbf{P}_p, \mathbf{P}_{-p}) = \arg \max_{\mathbf{P}_p} \Pi_p(\mathbf{P}_p, \mathbf{P}_{-p}) \quad (8)$$

By exploring the properties of Eq. 5 and Eq. 6, we can confirm the following properties for the best response function, defined in Eq. 8: $\mathcal{B}_p(\mathbf{P}_p, \mathbf{P}_{-p}) > 0, \forall \mathbf{P}_p > 0$, (ii) monotonicity: if $\mathbf{P}_p > \mathbf{P}_p'$, then $\mathcal{B}_p(\mathbf{P}_p, \mathbf{P}_{-p}) > \mathcal{B}_p(\mathbf{P}_p', \mathbf{P}_{-p})$, and (iii) scalability: for all $\xi > 1$, it holds true that $\xi \mathcal{B}_p(\mathbf{P}_p, \mathbf{P}_{-p}) \geq \mathcal{B}_p(\xi \mathbf{P}_p, \mathbf{P}_{-p})$. Based on this analysis, we conclude that the best response function $\mathcal{B}_p(\mathbf{P}_p, \mathbf{P}_{-p})$ is a standard function, and the non-cooperative game G converges to the Nash Equilibrium. Towards practically determining the Nash Equilibrium, the set of linear equations $\frac{\partial \Pi_p(\mathbf{P}_p, \mathbf{P}_{-p})}{\partial P_{p,a}} = 0$ can be analyzed, following typical numerical methods, such as the gradient method.

Concluding the above analysis, we have introduced and analyzed a fully competitive market model and determined the optimal prices $P_{p,a}^*, \forall p \in \mathcal{P}, \forall a \in \mathcal{A}$ following a non-cooperative game-theoretic approach while considering the CPs' CPR cache memory demand, as derived by the solution of the optimization problem (1a) – (1c).

IV. OLIGOPOLY MARKET MODEL

In this section, we focus our analysis on studying the ICNs interactions in order to decide the optimal prices of the CPR cache memory, per each of their serving areas, under the oligopoly market model. The core ICN provider is characterized by a larger coverage area and more available routers, respectively, in order to cache the CPs' content. Thus, the core ICN provider can act as a leader in the CPR cache memory market deciding its optimal prices per area. Then, the access and regional ICNs, which are characterized by smaller coverage areas and caching routers infrastructure compete among each other, and obviously, with the core ICN provider, to get a share of the CPs' CPR cache memory demand and ultimately maximize their personal profit, as defined in Eq. 6.

This interaction among the ICNs can be captured as a single-leader multiple-followers Stackelberg game, where the core ICN provider act as the leader and the access and regional ICNs are the followers. The core ICN provider announces first its optimal prices of the CPR cache memory at each of its serving areas, given the prices of the access and regional ICNs, aiming at maximizing its personal profit, as follows:

$$\mathcal{B}_C(\mathbf{P}_C, \mathbf{P}_{-C}) = \mathbf{P}_C^* = \arg \max_{\mathbf{P}_C} \Pi_C(\mathbf{P}_C, \mathbf{P}_{-C}) \quad (9)$$

where $\mathbf{P}_{-C} = [\mathbf{P}_A, \mathbf{P}_R]$.

The access and regional ICNs participate in a non-cooperative game among each other in order to determine their own optimal prices for leasing their CPR cache memory resources to the CPs, given the optimal price $\mathbf{P}_C^*$ announced by the core ICN provider. The non-cooperative game among the access and regional ICNs can follow similar formulation

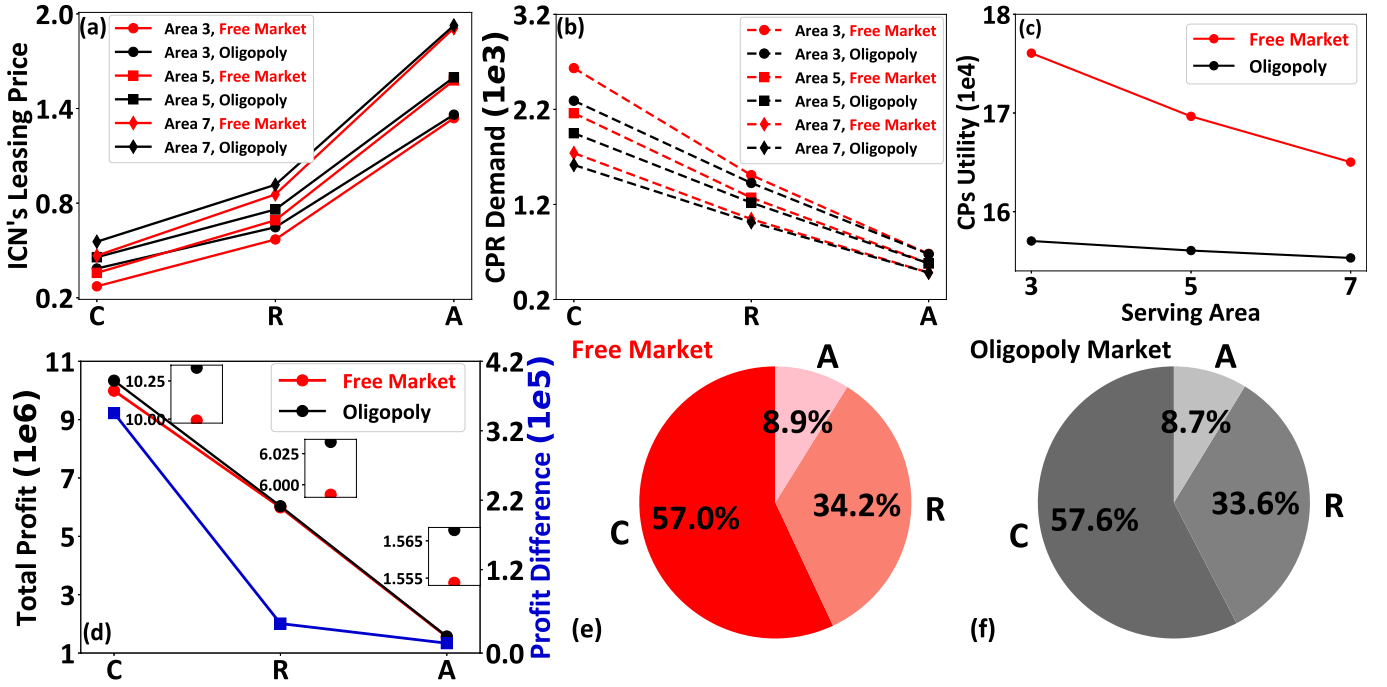


Fig. 2: Pure operation and performance of the symbiotic content caching framework.

and analysis in Section III, and their best response functions can be derived as follows:

$$B_A(\mathbf{P}_A, \mathbf{P}_{-A}) = \mathbf{P}_A^* = \arg \max_{\mathbf{P}_A} \Pi_A(\mathbf{P}_A, \mathbf{P}_{-A}) \quad (10)$$

$$B_R(\mathbf{P}_R, \mathbf{P}_{-R}) = \mathbf{P}_R^* = \arg \max_{\mathbf{P}_R} \Pi_R(\mathbf{P}_R, \mathbf{P}_{-R}) \quad (11)$$

Similar to the analysis presented in Section III, we can show that the non-cooperative game among the access and the regional ICNs has at least one Nash Equilibrium, and the ICNs' best response functions are standard functions, thus, the Nash Equilibrium can be determined, as the non-cooperative game converges to it. The two-step Stackelberg game is repeated iteratively and converges to a Stackelberg Equilibrium. The Stackelberg Equilibrium can be practically determined by adopting existing numerical methods, such as the gradient method.

V. EVALUATION & RESULTS

The performance of the proposed symbiotic content caching framework in next-generation information-centric networking systems is evaluated by extensive simulations. Specifically, in Section V-A, a detailed analysis of the pure performance and the operation of the proposed symbiotic content caching model is provided under the competitive market and the oligopoly market models in order to demonstrate its operational characteristics and identify the benefits and drawbacks of each market model. In Section V-B, a detailed scalability analysis is provided in order to show the efficiency and robustness of the proposed model. Finally, in Section V-C, a comparative evaluation of the proposed model to the state-of-the-art is presented in order to capture the superiority of the symbiotic content caching model under different scenarios

of the content providers' sensitivity to the caching slices' leasing price. The simulation parameters are listed as follows: $|\mathcal{A}| = 7$, number of users per area in the serving areas 1 - 7 is $[80, 70, 70, 60, 60, 50, 50]$, $P_f = [20, 25, 30] [\frac{\$}{Mbytes}]$, $\alpha_A = \alpha_R = \alpha_C = 2000$, $\beta_A = -100.23$, $\beta_R = -50.11$, $\beta_C = -33.36$, $\gamma = 2.97$, $\epsilon = 0.79$, $\zeta = 1.29$, $\mu_A^i = 0.01$, $\mu_R^i = 0.02$, $\mu_C^i = 0.03$, $\mu_{A,C}^i \in [0.02, 0.032]$, $\mu_{C,R}^i \in [0.025, 0.04]$, $\mu_{A,R}^i \in [0.03, 0.048]$, $d_p = [20, 15, 10]\%$, $B_p^{safe} = [100, 50, 30]$, unless otherwise explicitly stated.

A. Operation and Performance of Symbiotic Content Caching

Fig. 2a - 2b present the leasing price of the CPR cache memory announced by the ICN provider, and the CPs' total demand for each CP in three indicative serving areas, i.e., 3, 5, 7, where all the CPs serve the users simultaneously, respectively, under the competitive (free) market and oligopoly market model. Also, Fig. 2c presents the CPs' utility per serving area under the two market models, while Fig. 2d presents the ICNs' total profit in all serving areas, and the ICNs' profit difference under the two market models. Fig. 2e - 2f illustrate the percentage market-share profit of the ICNs under the free market and the oligopoly market models, respectively.

The results show that the higher the area's ID, the lower the demand for caching slices (Fig. 2b), given that the number of users in areas with higher ID is lower. This observation drives the proposed symbiotic content caching model to announce higher prices to areas with higher ID (Fig. 2a), given the lower demand in content caching slices under both market models. Also, we observe that the core ICNs support a higher demand of CPR caching slices requested by the CPs compared to the regional ICNs and to the access ICNs (Fig. 2b), given the respective higher availability of routers infrastructure. The

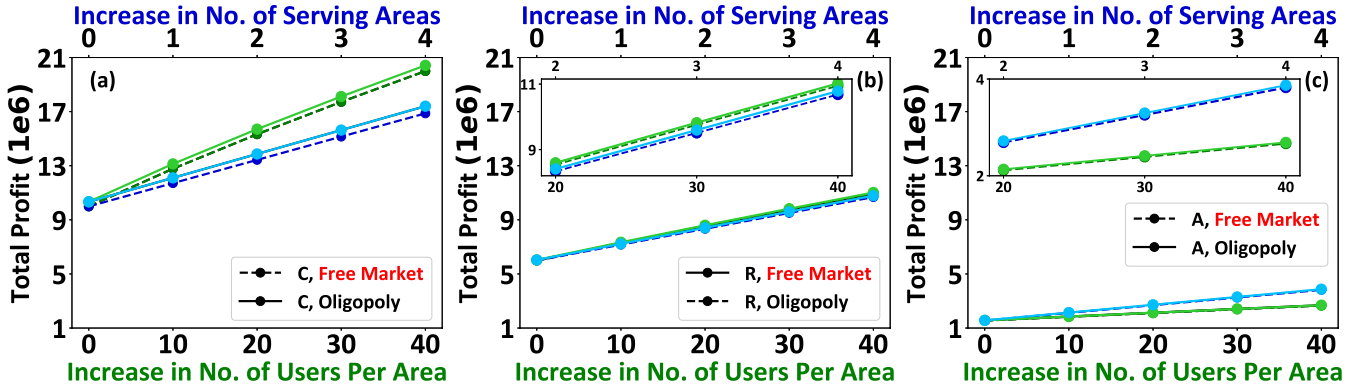


Fig. 3: Scalability analysis regarding ICNs total profit.

latter enables the core ICNs to announce a lower leasing price for the caching slices compared to the other ICNs under both market models (Fig. 2a). Furthermore, we observe that under the oligopoly market model, all the ICNs announce a higher price compared to the free market model (Fig. 2a), given the limited competition among them, resulting in a lower demand for caching slices from the CPs (Fig. 2b).

Focusing on Fig. 2c - 2d, we observe that the oligopoly market model benefits the ICNs in terms of achieving a higher profit (Fig. 2d), resulting in a substantially lower utility for the CPs (Fig. 2c), who are burdened with a higher leasing price for the resource of CPR caching slices. It is worth noting that the profit of the core ICN provider under the oligopoly market model is significantly higher compared to the corresponding profit achieved under the free market model as compared to the other ICN providers (Fig. 2d). This observation stems from the fact that the core ICN acts as the leader in the oligopoly market model, announcing first the leasing price of the caching slices and driving the market in a Stackelberg equilibrium that substantially benefits itself. This observation is further highlighted in Fig. 2e - 2f that present the percentage market-share profit of the ICNs under the free market and the oligopoly market models, respectively. The results show that in the oligopoly market model, the core ICN achieves a higher percentage market-share profit compared to the free market scenario (Fig. 2f) and compared to the other ICNs, while it should also be noted that the overall profit under the oligopoly market model is substantially higher compared to the free market model, as presented in Fig. 2d.

B. Scalability Analysis

In this section, a scalability analysis is considered by studying two different scenarios. Specifically, we consider the scenario where the number of users per serving area increases with a constant step of 10 users added per area (green scenario), and the scenario that an equivalent increase of the number of users is captured by adding a new serving area in the overall system (blue scenario). Fig. 3a - 3c present the total profit of the core, regional, and access ICN providers, respectively, under both scalability analysis scenarios for the free market and the oligopoly market models. Fig. 4a - 4b illustrate the corresponding CPs' average utility under both

scalability analysis scenarios considering the free market and the oligopoly market models, respectively.

The results reveal that as the number of users increases under both scalability analysis scenarios, the profit of all the ICN providers increases under both market models (Fig. 3). However, it is observed that the increase in the number of users per area is more beneficial for the core and the regional ICNs (Fig. 3a - 3b), which are characterized by higher routers infrastructure availability compared to the access ICN provider. On the other hand, the scalability analysis scenario where the number of serving areas increases benefits the access ICN provider (Fig. 3c), which is capable of competing in more serving areas with additional routers infrastructure, thus, making this provider more competitive in the content caching market. Also, the results reveal that the oligopoly market model results in higher total profit for all the ICN providers under both scalability analysis scenarios (Fig. 3).

Focusing on CPs average utility, as presented in Fig. 4a - 4b under the free market and oligopoly market models, respectively, we observe that the free market model benefits the users under both scalability analysis scenarios, as the ICNs compete among each other to determine the CPR caching slices leasing price within a fully competitive market, thus, lowering the resulting leasing prices. Also, the results reveal that as the number of users increases (green scenario), the CPs average utility decreases under both market models (free market and oligopoly), as a larger number of users compete for the same CPR caching slices resources. On the other hand, as the number of users increases, but also the number of serving areas increases (blue scenario), the average utility of the CPs increases as more CPR caching slices resources become available in the market under both market models.

C. Comparative Evaluation

In this section, a comparative evaluation analysis is provided considering the CPs' sensitivity characteristics to the changes of the ICNs' CPR caching slices leasing price. Specifically, the proposed symbiotic content caching model is compared to two alternative scenarios: (i) Scenario A: all the CPs are characterized by the same sensitivity to the CPR caching slices leasing price per area, however, the sensitivity parameters are personalized to each CP, and (ii) Scenario B: all the CPs

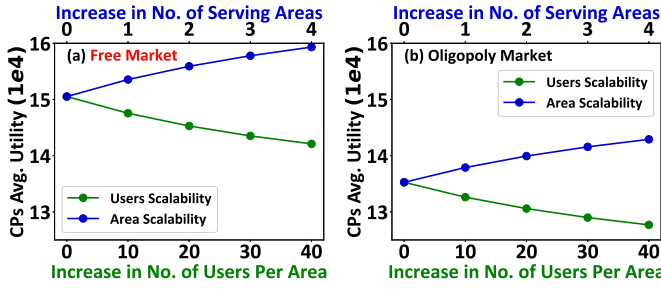


Fig. 4: Scalability analysis regarding CPs average utility.

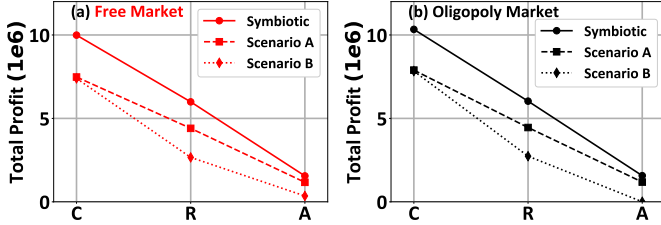


Fig. 5: Comparative evaluation.

are characterized by the same sensitivity to the leasing price changes in all the serving areas. The results reveal that the personalized treatment of the CPs, regarding their sensitivity characteristics to the CPR caching slices leasing price, results in higher total profit for the CPs both under the free market and the oligopoly market models.

VI. CONCLUSION AND FUTURE WORK

In this paper, a novel symbiotic content caching framework is introduced in next-generation information-centric networking systems in order to jointly support the cost-efficient leasing of caching slices for the CPs and maximize the ICNs profit. Specifically, a novel ICN architecture is introduced considering the core, regional, and access ICN providers in order to decrease the delay of the first-control requests by the users. Based on the novel ICN architecture, a symbiotic content caching model is introduced by capturing the mutualistic interactions among the ICNs and the CPs under the prism of the competitive market and oligopoly market models. A game-theoretic approach is proposed in order to determine the optimal leasing prices of the ICNs' content caching slices and the CPs' optimal amount of leased caching memory from the ICNs. A detailed simulation-based evaluation is provided to demonstrate the operational characteristics of the proposed model and highlight its benefits. Part of our current and future work is the extension of the proposed model in 3D networks, where content can be cached in Unmanned Aerial Vehicles (UAVs) and High Altitude Platforms (HAPs).

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