# Mutualistic Compute Continuum: A Network Economics Analysis

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***Abstract*—In the transformative data-driven era, Compute Continuum – consisting of the edge, fog and cloud - has been introduced as a viable long-term economic model. In this setting the problem of utilizing the appropriate compute resources at optimal processing points (edge, fog, cloud) in the system, becomes of paramount importance. In this paper, we address this issue by introducing the novel concept of mutualistic computing. Specifically, we do not simply account for the interactions among the involved actors, but we consider that the edge, fog, and the cloud computing providers establish an obligate symbiosis with the users in order to serve their computing demands. A network economics-based analysis is introduced in order to jointly enable the computing providers and the users to maximize their profit and utility, respectively. Two pricing models are studied to determine the computing providers' optimal prices in terms of maximizing their profit. The first one - free market pricing model - enables the full competition among the computing providers and is formulated as a non-cooperative game among the computing providers. The second one - oligopoly pricing - is introduced among the cloud computing provider (leader) and the edge, fog computing providers (followers), and is treated via a Stackelberg game. The performance evaluation of the proposed approach is achieved via modeling and simulation, and the tradeoffs of the two different pricing models within the mutualistic computing paradigm are highlighted.**

***Index Terms*—Network Economics, Mutualistic Computing, Compute Continuum, Game Theory.**

## I. Introduction

The explosive growth of Internet of Things (IoT) and the number of connected devices, as well as the advent of next-generation applications, such as virtual/augmented reality, Tactile Internet, have jointly contributed to an unprecedented need for computing resources [1]. Towards addressing the increased computing demand, the Compute Continuum has been introduced as a viable solution, consisting of the edge, fog, and cloud computing resources [2], [3]. In this paper, we introduce the novel concept of *mutualistic computing* in the Compute Continuum era, where the edge, fog, and the cloud computing providers establish an obligate symbiosis with the users in order to serve their computing demands [4]. A network economics analysis is provided considering the free market and oligopoly pricing models for the computing providers, aiming at maximizing their profit, while simultaneously maximizing the users' utility from the provided computing resources.

### A. Related Work

Several studies have been conducted in the field of resource allocation and pricing in edge, fog, and cloud computing environments. Focusing on *cloud computing*, a price bidding mechanism is introduced in [5] among the cloud providers and is formulated as a non-cooperative game. The Nash equilibrium is determined concluding to the optimal price announced by each cloud provider that maximizes its benefit from the consumers. A reinforcement learning-based pricing mechanism is introduced in [6] enabling the cloud providers to decide the prices that jointly optimize their profit and cost. The novel aspect of this research work is that it accounts for the users' personality and Quality of Service (QoS) satisfaction, while designing the pricing decision-making algorithm for the cloud providers. An incentive-based auction pricing model is proposed in [7], which incentivizes the users to purchase computing resources from the cloud computing providers while guaranteeing a minimum profit rate for the later ones.

Focusing on the *edge computing* paradigm, the optimization of the edge computing provider's (ECP) profit is formulated as a mixed-integer programming problem in [8] aiming at jointly determining an optimal resource allocation and pricing. Given the complexity of solving this problem, a greedy-and-search-based iterative algorithm is proposed to determine the optimal solution. A Stackelberg game-theoretic approach is presented in [9] among the ECPs (leaders) and the users (followers). The ECPs determine their optimal prices to maximize their revenue, while the users select an ECP that will be served from, considering the announced price. Three dynamic pricing schemes for the ECPs are discussed in [10] based on a bidding, uniform, and a fairness-seeking differentiated pricing model, respectively. A detailed comparative evaluation is provided, highlighting the drawbacks and benefits of each model.

Limited research efforts have been devoted to the pricing models in a *joint edge, fog, and cloud computing* environment. In [11], the interactions among the edge servers and the cloud provider are studied following a Stackelberg game-theoretic approach. The cloud provider (leader) determines the optimal price to maximize its profit while the edge servers determine the optimal amount of offloaded computing tasks to the

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cloud. A double-layer Stackelberg game-theoretic approach is discussed in [12] among the cloud provider, edge servers, and users, aiming at optimizing the benefit of each involved entity, via determining the optimal announced prices by the cloud and edge computing providers. In [13], a multi-ECP market is studied based on a Stackelberg game-theoretic approach among the ECPs (leaders) and the users (followers). The proposed model determines the optimal price of each ECP to maximize its profit, and the optimal partial task offloading for each user to maximize its utility.

### *B. Contributions & Outline*

The aforementioned research works have concentrated on designing pricing models, either among the cloud and the users, or the cloud and the edge, or the edge and users, thus addressing the problem in a rather fragmented manner. Therefore, none of the existing studies have designed a pricing model for the whole Compute Continuum, ranging from the edge to the fog to the cloud. More fundamentally, the simultaneous interactions of the users with the computing providers in the Compute Continuum in order to conclude to an operational computing environment, where each involved entity optimizes its benefit, has not been studied in the existing literature. This article fills this gap by introducing the novel concept of mutualistic computing in the Compute Continuum era based on a network economics analysis. Our main contributions are listed as follows.

1) The obligate symbiosis among the edge, fog, cloud computing providers and the users is introduced where none of those entities can operate without the other, thus, they engage in a mutualistic partnership. Based on this analysis, the novel concept of mutualistic computing is proposed following the principles of evolution in biological ecosystems. Each mutualistic partner aims to maximize its benefit. Specifically, the users and the computing providers aim to maximize their utility from purchasing the computing resources, and their profit from offering computing services, respectively.
2) Two pricing models are studied to determine the computing providers' optimal prices in terms of maximizing their profit. The *free market* pricing model is introduced enabling full competition among the computing providers in order to determine their optimal prices while addressing the users' computing needs. The free market pricing model is formulated as a non-cooperative game among the computing providers and the existence of a Nash equilibrium is shown.
3) Second, an *oligopoly* pricing model is introduced among the cloud computing provider (leader) and the edge, fog computing providers (followers). The oligopoly market model is captured via a Stackelberg game-theoretic model and the Stackelberg equilibrium is determined, thus, calculating the optimal prices of the computing providers.
4) A detailed network economics-based analysis is performed, highlighting the drawbacks and benefits of the free market versus the oligopoly pricing model in the mutualistic computing paradigm.


Fig. 1: Mutualistic computing paradigm in the Compute Continuum era.

The novel concept of the mutualistic computing in the Compute Continuum era is presented in Section II. The free market and oligopoly pricing models are presented in Sections III and IV, respectively. A detailed network economics analysis via a numerical evaluation is provided in Section V, and finally Section VI concludes the paper.

## II. Mutualistic Computing

### *A. A Biological Analogy*

Following the operational principles of a biological ecosystem, two or more organisms can not survive one without the other, thus, they engage in an obligate symbiosis. Among the different types of obligate symbioses, e.g., commensalism, parasitism, the mutualistic obligate symbiosis presents great interest. Under mutualistic symbiosis, an organism can offer a resource to the other organisms, and the latter ones provide a service as a reward. A well-known mutualistic relationship is the one between the clownfish and the anemones. Clownfish are immune to anemone stings in contrast to other small sea animals, thus, the clownfish can hide in anemone's stings from potential predators, and also attract other fish looking for a meal, via their bright color which will be trapped by the anemone for ingestion. On the other hand, the anemone provides shelter to the clownfish as a service. Following this mutualistic anology from the biological ecosystems, the edge, fog, and cloud computing providers, called Mutualistic Computing Components (MCCs), provide their computing resources to the users, i.e., acting as the clownfish, while the users provide a reward via the price that they pay, i.e., acting as the anemone. The MCCs and the users are called mutualistic partners, given that they engage into the mutualistic relationship. The users need the MCCs to support their computing demand, and the MCCs need the users to purchase their computing resources in order to stay in business.

### B. System Model

The MCCs provide safe computing resources, e.g., virtual machines, and a Common Pool of Computing Resources (CPCRs), e.g., serverless computing. We denote the set of MCCs as $I = \{C, F, E\}$, i.e., the cloud ($C$), fog ($F$), edge ($E$) computing providers. For the safe computing resources, the price is fixed per each MCC $P_i^{safe}[\frac{\$}{CPU-Cycles}], \forall i \in I$, which allocates sufficient computing resources to each offloaded computing task by each user in order to guarantee the users' QoS prerequisites satisfaction. For the CPCR, the price is variable, and depends on the users' computing demand and the competitive behavior of the MCCs in the computing market. The MCCs price vector for the CPCR is $\mathbf{P} = [\mathbf{P}_C^{CPCR}, \mathbf{P}_F^{CPCR}, \mathbf{P}_E^{CPCR}][\frac{\$}{CPU-Cycles}]$. Given the risky nature of the CPCR in terms of its availability, the pricing of the CPCR is lower compared to the safe computing resources, which are exclusively allocated to the users [14].

In the following analysis, we consider an indicative topology of the Compute Continuum (Fig. 1), showing the different coverage areas of the MCCs. Also, for greater generality in our analysis, we consider that all the MCCs are independent and their goal is to maximize their profit via providing computing services to the users. In the general case, each user requests two types of applications, i.e., critical and elastic applications. For critical applications, the user allocates a part of its budget to purchase safe computing resources, while for its elastic applications, the user opportunistically shapes its demand based on its computing needs and the MCCs' prices.

### C. Mutualistic Partners Characteristics

Each user's goal is to maximize its resource profit by exploiting the MCCs' CPCR that serve its area:

$$\textbf{P1:} \quad \max_{b_{u,i}} [\mathcal{U}_u(\mathbf{P}) - \sum_{\forall i \in I} P_{i,a}^{CPCR} \cdot b_{u,i}] \tag{1a}$$

$$\text{s.t.} \quad P_{i,a}^{CPCR} \geq 0, \forall i \in I, \forall a \in A_i \tag{1b}$$

$$b_{u,i} \geq 0 \tag{1c}$$

where $b_{u,i}[CPU - Cycles]$ is the CPCR allocated by the MCC $i$ to the user $u$. We denote as $U = \{1, \dots, u, \dots, |U|\}$ the set of users requesting services in the examined Compute Continuum and as $U_a \subseteq U$ the set of users residing in area $a$, and the sets of areas that each MCC serves as $A_i, A_j, A_k$. For example, we have $A_i = \{1, 2, \dots, 7\}$ for the cloud, $A_j = \{2, 3, \dots, 7\}$ for the fog, and $A_k = \{3, 5, 7\}$ for the edge computing provider. The users' pure utility $\mathcal{U}_u(\mathbf{P})$ can be defined as a quadratic and strictly concave function, where the corresponding computing demand is linear by extending the Singh and Vives model [15], as follows:

$$\mathcal{U}_u(b_{u,i}, b_{u,j}, b_{u,k}) = \alpha_i b_{u,i} + \alpha_j b_{u,j} + \alpha_k b_{u,k} - \frac{\beta_i b_{u,i}^2}{2} - \frac{\beta_j b_{u,j}^2 + \beta_k b_{u,k}^2 + 2\gamma b_{u,i} b_{u,j} + 2\epsilon b_{u,j} b_{u,k} + 2\zeta b_{u,i} b_{u,k}}{2} \tag{2}$$

where the coefficients are real numbers and their relative values can be derived by the following analysis and $i, j, k \in I$, with $i \neq j \neq k$. Towards solving the optimization problem (1a) – (1c), we solve the set of linear equations that are derived from $\frac{\partial}{\partial b_{u,i}}[\mathcal{U}_u(b_{u,i}, b_{u,j}, b_{u,k}) - \sum_{\forall i \in I} P_{i,a}^{CPCR} \cdot b_{u,i}] = 0, \forall i \in I$. Initially, we determine the determinants $D_{b_{u,i}}, D_{b_{u,j}}, D_{b_{u,k}}, D$ and by solving the system of inequalities $D_{b_{u,i}} > 0, D_{b_{u,j}} > 0, D_{b_{u,k}} > 0, D > 0$ we determine the relative values of all the coefficients included in Eq. 2. Then, we determine the optimal purchased CPCR from user $u$ from each MCC $i, \forall i \in I$, as $b_{u,i}(\mathbf{P}) = B_{u,i} - \mu_i^u P_{i,a}^{CPCR} + \mu_{i,k}^u P_{k,a}^{CPCR} + \mu_{i,j}^u P_{j,a}^{CPCR}$, where, $B_{u,i} = \frac{\beta_j \beta_k \alpha_i + \lambda_{j,k}^2 \alpha_i + \lambda_{j,i} \beta_k \alpha_j - \lambda_{k,j} \lambda_{k,i} \alpha_j - \lambda_{j,i} \lambda_{k,j} \alpha_k + \lambda_{k,i} \alpha_k \beta_j}{D}$, with $\lambda_{i,j} = \gamma, \lambda_{j,k} = \epsilon, \lambda_{i,k} = \zeta, D = -\beta_i(\beta_j \beta_k - \lambda_{j,k}^2) + \lambda_{i,j}(\lambda_{i,j}\beta_k - \lambda_{j,k}\lambda_{i,k}) - \lambda_{i,k}(\lambda_{j,k}\lambda_{i,j} - \beta_j \lambda_{i,k}), \mu_i^u = \frac{\beta_k \beta_j - \lambda_{k,j}^2}{D}, \mu_{i,k}^u = \frac{\lambda_{k,j}\lambda_{k,i} - \lambda_{j,i}\beta_k}{D}, \mu_{i,j}^u = \frac{\lambda_{j,i}\lambda_{k,j} - \lambda_{k,i}\beta_j}{D}$ and applying the index rotation for the general case. Focusing on the users' aggregated CPCR computing demand in a serving area $a$, it can be calculated as $D_{i,a}(\mathbf{P}) = \sum_{\forall u \in U_a} b_{u,i}(\mathbf{P})$, and for notation convenience, it can be written as follows:

$$D_{i,a} = B_{i,a} - \mu_i^a P_{i,a}^{CPCR} + \mu_{i,k}^a P_{k,a}^{CPCR} + \mu_{i,j}^a P_{j,a}^{CPCR} \tag{3}$$

where $B_{i,a}[CPU - Cycles]$ denotes the users CPCR computing demand in area $a$ from the MCC $i, \forall i \in I$. The physical meaning of the $\mu_i^a$ coefficient captures the sensitivity of the users' CPR computing demand to a price change, when being served by MCC $i$. The physical meaning of the $\mu_{i,k}^a$ and $\mu_{i,j}^a$ reflects the portion of CPR computing demand that flows from MCC $k$ and $j$ to MCC $i$ for a given price offered by the MCC $k$ and $j$, respectively. The profit of each MCC $i, \forall i \in I$, at an area $a$ can be defined as follows.

$$PR_{i,a}(P_{i,a}^{CPCR}, \mathbf{P}_{-i,a}^{CPCR}) = D_{i,a} P_{i,a}^{CPCR} + N_{i,a}^{safe} P_i^{safe} - N_{i,a}^{safe} d_i [B_i^{req} - \frac{B_{i,a} - D_{i,a}}{N_{i,a}^{safe}}]^2 \tag{4}$$

The first term of Eq. 4 represents the revenue of MCC $i$ by covering the aggregated CPCR computing demand $D_{i,a}$ at an announced price $P_{i,a}^{CPCR}$ at a serving area $a$. The second term of Eq. 4 captures the MCC $i$'s revenue from covering the $N_{i,a}^{safe}$ users safe computing demand at a serving area $a$. We consider that the safe computing demand is quantized, and each safe computing quantity has a fixed price for each MCC, e.g., request for a virtual machine. In general, $N_{i,a}^{safe}$ can be greater or smaller than $|U_a|$, but it will be an apriori known parameter in the system. The third term of Eq. 4 represents the discount offered by the MCC to the $N_{i,a}^{safe}$ users, if the MCC cannot satisfy their safe computing demand that the users have already paid for this requested service with a fixed price $P_i^{safe}$. The MCC $i$'s discount factor is denoted as $d_i\%$ of the price $P_i^{safe}$. The minimum safe computing resources prerequisite of the users from MCC $i$ is $B_i^{req}[CPU - Cycles]$. The MCC $i$'s overall profit by allocating its computing resources to the users $|U_a|$, $\forall a \in A_i$ is $PR_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) = \sum_{\forall a \in A_i} PR_{i,a}$.

## III. Free Market Pricing Model

In this section, we introduce a free market pricing model in the mutualistic computing paradigm, considering full competition among the MCCs in order to determine the optimal prices that maximize their profit, while supporting the users' computing demand. Given their full competition nature, the MCCs profit maximization problem can be formulated as a non-cooperative game among them. We denote as $G = [I, \{\mathcal{P}_i\}_{\forall i \in I}, \{PR_i\}_{\forall i \in I}]$ the non-cooperative game, where $I$ is the set of players, i.e., MCCs, $\mathcal{P}_i$ is the set of pricing strategies of each MCC $i$ for its CPCR, and $PR_i$ is the MCC $i$'s total profit. We denote as $\mathbf{P}_i^{CPCR}$ the price vector of MCC $i$ for all its serving areas. For example, based on Fig. 1, we have $\mathbf{P}_C^{CPCR} = [P_{C,1}, P_{C,2}, \ldots, P_{C,7}]$ for the cloud, $\mathbf{P}_F^{CPCR} = [P_{F,2}, P_{F,3}, \ldots, P_{F,7}]$ for the fog, and $\mathbf{P}_E^{CPCR} = [P_{E,3}, P_{E,5}, P_{E,7}]$ for the edge computing provider. Also, we denote as $\mathbf{P}_{-i}^{CPCR}$ the price vector of the prices of all the other MCCs except MCC $i$. The best response dynamics can be followed to determine a Nash Equilibrium $\mathbf{P}^*$.

*Definition 1:* **(Nash Equilibrium – NE):** The price vector $\mathbf{P}^* = [\mathbf{P}_C^{CPCR*}, \mathbf{P}_F^{CPCR*}, \mathbf{P}_E^{CPCR*}]$ is a Nash Equilibrium of the non-cooperative game $G$, if for every $i \in I$, $PR_i(\mathbf{P}_i^{CPCR*}, \mathbf{P}_{-i}^{CPCR*}) \geq PR_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR*}), \forall \mathbf{P}_i^{CPCR} \in \mathcal{P}_i$.

The best response function of the MCC $i$ is given as follows.

$$\mathcal{B}_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) = \arg\max_{\mathbf{P}_i^{CPCR}} PR_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) \quad (5)$$

Based on Eq. 4 and Eq. 5, it can be easily shown that the best response function $\mathcal{B}_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR})$ admits the properties of : (i) positivity: $\mathcal{B}_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) > 0$ considering that the safe computing resources discount is less than the revenue from these resources; (ii) monotonicity: if $\mathbf{P}_i^{CPCR} > \mathbf{P}_i^{CPCR'}$, then $\mathcal{B}_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) > \mathcal{B}_i(\mathbf{P}_i^{CPCR'}, \mathbf{P}_{-i}^{CPCR})$, and (iii) scalability: for all $\kappa > 1$, it holds true that $\kappa\mathcal{B}_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR}) \geq \mathcal{B}_i(\kappa\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR})$ [16]. Thus, the best response function is a standard function and at least one NE exists. The NE can be determined by solving the set of equations $\frac{\partial PR_i(\mathbf{P}_i^{CPCR}, \mathbf{P}_{-i}^{CPCR})}{\partial P_{i,a}^{CPCR}} = 0$, following any typical numerical method, such as the gradient method. The NE determines the optimal prices of the MCCs at each serving area considering the full competition among the MCCs under the free market pricing model.

## IV. Oligopoly Pricing Model

In this section, we study the mutualistic computing paradigm under the prism of an oligopoly market, where the cloud computing provider acts as a leader, given its higher computing capacity availability. The edge and fog computing providers act as followers to the price announced by the cloud, and all the MCCs interact among each other to shape the market price in order to converge to a smooth symbiosis. The oligopoly pricing model can be captured via a single-leader (cloud) multiple-followers (edge and fog) Stackelberg game. The Stackelberg equilibrium determines the prices of the cloud computing provider per serving area $a$, i.e., $\mathbf{P}_C^{CPCR}$, that maximize its profit $PR_c(\mathbf{P}_C^{CPCR}, \mathbf{P}_{-C}^{CPCR})$, and the prices announced by the edge $\mathbf{P}_E^{CPCR}$ and fog $\mathbf{P}_F^{CPCR}$ computing providers, as determined by the Nash Equilibrium of a non-cooperative game among them.

The leader, i.e., cloud computing provider, determines the optimal prices per area to maximize its profit, as follows.

$$\begin{aligned}\mathcal{B}_C(\mathbf{P}_C^{CPCR}, \mathbf{P}_{-C}^{CPCR}) &= \mathbf{P}_C^{CPCR*} \\ &= \arg\max_{\mathbf{P}_C^{CPCR}} PR_C(\mathbf{P}_C^{CPCR}, \mathbf{P}_{-C}^{CPCR})\end{aligned} \quad (6)$$

Then, the edge and the fog computing providers participate in a non-cooperative game among them, competing among each other in order to maximize their own profit. Their best response functions can be derived as follows for the edge (Eq. 7) and the fog (Eq. 8) computing provider.

$$\begin{aligned}\mathcal{B}_E(\mathbf{P}_E^{CPCR}, \mathbf{P}_{-E}^{CPCR}) &= \mathbf{P}_E^{CPCR*} \\ &= \arg\max_{\mathbf{P}_E^{CPCR}} PR_E(\mathbf{P}_E^{CPCR}, \mathbf{P}_{-E}^{CPCR})\end{aligned} \quad (7)$$

$$\begin{aligned}\mathcal{B}_F(\mathbf{P}_F^{CPCR}, \mathbf{P}_{-F}^{CPCR}) &= \mathbf{P}_F^{CPCR*} \\ &= \arg\max_{\mathbf{P}_F^{CPCR}} PR_F(\mathbf{P}_F^{CPCR}, \mathbf{P}_{-F}^{CPCR})\end{aligned} \quad (8)$$

The NE of the non-cooperative game among the edge and fog computing providers can be determined by following a similar approach, as the one presented in Section III. The Stackelberg game is repeated iteratively until it converges to the Stackelberg Equilibrium (SE). The SE can be determined by following a numerical method, such as the gradient method.

## V. Numerical Results

In this section, a detailed network economics-based analysis of the proposed mutualistic computing paradigm is provided under both the free market and oligopoly pricing models. Initially, in Section V-A, we validate the performance and operation of the two pricing models. A scalability analysis is then presented in Section V-B, both from the users' computing demand perspective, and the computing providers' profit. In Section V-C, a quantitative comparative study of the benefits of the proposed model compared to the state-of-the-art is provided. An indicative simulation topology is presented in Fig. 1. Unless otherwise explicitly stated, the specific system parameters used throughout our evaluation are as follows: $\mathbf{P}^{safe} = [1000, 1100, 1200][\frac{cents}{CPU-cycles}]$, $\alpha_i = 2 \times 10^3$, $\beta_i = -50.10, \beta_k = -66.82, \beta_k = -100.28$, $\epsilon = 3.26, \gamma = 1.59, \zeta = 2.42$, $U_a = [25, 20, 20, 15, 15, 10, 10]$, $\mathbf{N}_C^{safe} = [1, 2, 2, 3, 3, 4, 4]$, $\mathbf{N}_F^{safe} = [3, 3, 4, 4, 5, 5]$, $\mathbf{N}_E^{safe} = [4, 5, 6]$, $B_C^{req} = 30$, $B_F^{req} = 20$ , $B_E^{req} = 10[GCPU - Cycles]$, $d_C = 30\%$, $d_F = 15\%$, $d_E = 10\%$.

### A. Pure Operation & Performance

In this section, we demonstrate the operational characteristic and the effectiveness of the proposed mutualistic computing paradigm in terms of optimizing the computing providers (cloud, fog, edge) profit, while adapting to the users' computing demand. Fig. 2a - 2b show the MCCs' optimal price and

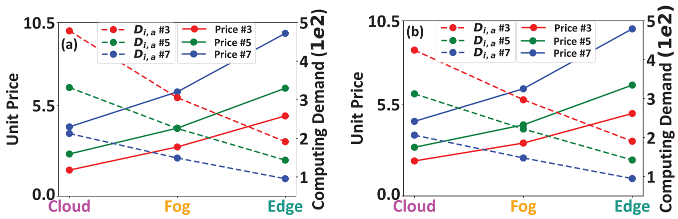


Fig. 2: Pure operation and performance of the (a) free market and (b) oligopoly pricing models.

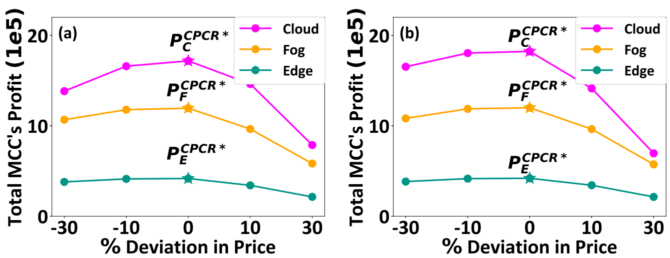


Fig. 3: Optimal prices under the (a) free market and (b) oligopoly pricing models.

the users' aggregated computing demand for the free market and oligopoly pricing models, respectively. Three indicative areas # 3, 5, 7 are studied, where all the MCCs coexist and compete with each other in the computing service market. It is noted that the higher the service area's ID, the lower the users' CPCR computing demand $B_i^a$, as it can be derived by their personal coefficients in Eq. 2.

Based on Fig. 2a - 2b, we initially observe that the scarcer the MCCs' computing resources become, i.e., ranging from the cloud to the fog to the edge computing provider, the higher the announced price by the MCC given the limited availability of resources both for the free market (Fig. 2a) and the oligopoly (Fig. 2b) models. Also, given the increased price, in combination with the limited computing resources of the MCCs, ranging from the cloud to the fog to the edge, the corresponding users' computing demand decreases under both pricing models. Furthermore, the higher the service area's ID, the lower the initial users' demand $B_i^a$, and the total aggregated demand $D_{i,a}$ (Eq. 3) follows the same trend, as it is shaped by the announced prices of the MCCs under both pricing models. Focusing on the comparison of the free market vs. oligopoly, we observe that under the oligopoly pricing model, the prices are slightly increased for all the service areas (Fig. 2b). The price increase under the oligopoly pricing model drives the slight decrease of the aggregated CPCR computing demand (Fig. 2b).

Fig. 3a - 3b illustrate the behavior of the MCCs' total profit as a function of the percentage deviation from the optimal announced price $\mathbf{P}_i^{CPCR*}, \forall i \in I$, for the free market and oligopoly pricing models, respectively. The results reveal that under both pricing models, the MCCs cannot achieve a higher profit if they deviate from the Nash Equilibrium (free market model, Fig. 3a) or the Stackelberg Equilibrium (oligopoly model, Fig. 3b). Also, the results show that the free market model drives the MCCs to decrease their prices compared to

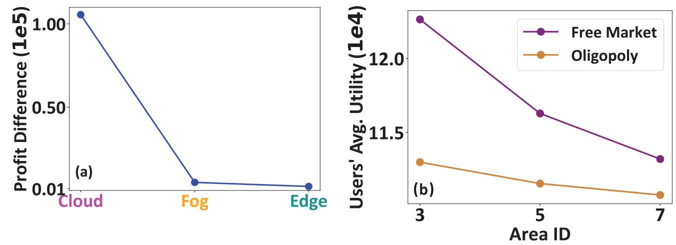


Fig. 4: Comparison of (a) total MCCs' profit and (b) users' average utility under the free market and oligopoly pricing models.

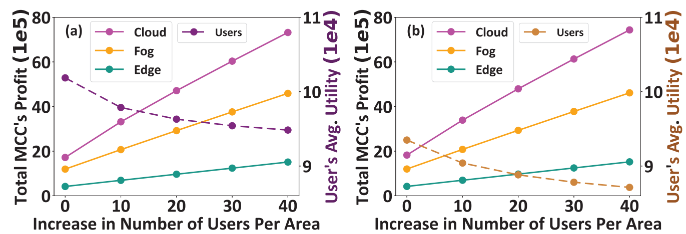


Fig. 5: Computing providers' profit scalability under the (a) free market and (b) oligopoly pricing models.

the oligopoly model (Fig. 2), resulting in lower computing costs for the users, but also lower profit for MCCs (Fig. 3). Furthermore, Fig. 4a - 4b illustrate the MCCs' profit difference under the oligopoly and free market models and the users' average utility per area, respectively. The results show that all the MCCs achieve a substantially higher profit under the oligopoly market model (Fig. 4a), resulting in a lower average utility for the users (Fig. 4b), who experience a higher price in order to purchase the CPCR resources. Also, by taking a closer look at the results of Fig. 4a, we observe that the cloud provider substantially benefits in terms of profit-making under the oligopoly market model, given that it acts as a leader in the market compared to the fog and edge computing providers.

### B. Scalability Analysis

In this section, a detailed scalability analysis is provided both from the users' average utility, and the total MCCs' profit perspective, under the free market and oligopoly pricing models. Fig. 5a - 5b present the total MCC's profit and the users' average utility in all the examined areas under the scenarios of free market and oligopoly market, respectively, for an increasing number of users, where the value 0 represents the baseline scenario, i.e., $U_1 = 25$, $U_2 = 20$, $U_3 = 20$, $U_4 = 15$, $U_5 = 15$, $U_6 = 10$, and $U_7 = 10$. The results show that as the number of users increases, the total MCCs' profit also increases under both market models, as more users are purchasing computing resources. However, under the oligopoly market model (Fig. 5b), the MCCs achieve to make higher profit compared to the the free market model (Fig. 5a), as the unit price of the CPCR resource is higher, as explained in Section V-A. Driven by the latter observation, the users' average utility decreases faster under the oligopoly market model (Fig. 5b) as a function of the number of users requesting computing resources, given the higher announced

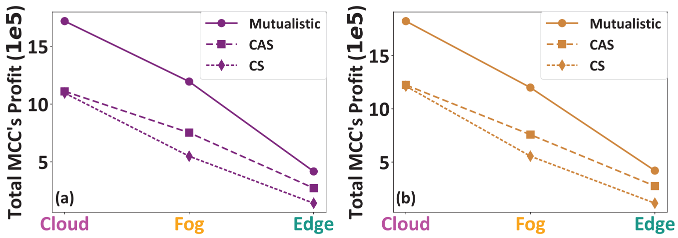


Fig. 6: Comparative evaluation.

unit price of the CPCR resource. Also, it is noted that under both market models, the users' average utility decreases as the number of users in the areas increase, given that a larger number of users share the same common pool of computing resources.

### C. Comparative Evaluation

In this section, we provide a detailed comparative evaluation in order to demonstrate the drawbacks and benefits of the proposed mutualistic computing paradigm in the Compute Continuum under both the free market and oligopoly market modeling. Specifically, the proposed mutualistic computing paradigm is compared to two alternative scenarios, regarding the users' sensitivity to the common pool of computing resources' price changes, and its impact on the total MCCs' profit. The two examined comparative scenarios are: (a) Common Area Sensitivity (CAS): all the users present the same sensitivity to the announced price of the common pool of computing resources per area, and, each user is characterized by personalized sensitivity metrics, as captured in Eq. 2; (ii) Common Sensitivity (CS): all the users present the same sensitivity to the price changes of the common pool of computing resources in all the examined areas. The results show that our proposed mutualistic computing paradigm that treats the users in a personalized manner in each area within the Compute Continuum, regarding their price sensitivity, achieves the highest total profit for the MCCs under both the free market (Fig. 6a) and the oligopoly market (Fig. 6b) modeling. By taking a closer look at the results, we also observe that the Common Sensitivity scenario, which ignores the users' personalized sensitivity to the common pool of computing resources' price change, results in the lowest profit-making for the MCCs under both examined market models. Finally, it is again confirmed that under all the aforementioned comparative scenarios, the MCCs achieve higher profits under the oligopoly market modeling.

## VI. Conclusion

In this paper, inspired by the operation of the biological ecosystems we introduce the novel concept of mutualistic computing within the Compute Continuum, by studying the mutualism relationship among the cloud, edge, fog computing providers and the users. A network economics-based analysis is introduced in order to jointly enable the computing providers and the users to maximize their profit and utility, respectively. Two types of computing pricing markets are studied. The free market pricing model is captured as a non-cooperative game among the computing providers and its Nash Equilibrium is determined in order to calculate the computing providers' optimal prices. The oligopoly pricing model is studied via a Stackelberg game-theoretic approach among the cloud (leader) and the edge, and fog computing providers (followers). The Stackelberg Equilibrium is determined and the optimal prices of the computing providers are derived. A detailed performance evaluation is performed, and the drawbacks and benefits of the free market versus the oligopoly pricing model are highlighted. Our current and future work focuses on extending the mutualistic concept in a jointly integrated computing and communication system, studying the interdependencies between communication and computing resources.

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