On the Economics of Fog Computing: Inter-play among Infrastructure and Service Providers, Users, and Edge Resource Owners

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***Abstract*—Fog computing is a paradigm which brings computing, storage, and networking closer to end users and devices for better service provisioning. One of the crucial factors towards the success of fog computing is how to incentivize the individual users' edge resources, thereby opening the era of user-participated fog computing. In this paper, we provide an economic analysis of such user-oriented fog computing by modeling a market consisting of ISP (Infrastructure and Service Provider), SUs (end Service Users), and EROs (Edge Resource Owners) as a non-cooperative game. In this market, ISP, which provides a platform of fog computing, behaves as a mediator or a broker to lease the edge resources from EROs and provide various services to SUs. In our game formulation, a two-stage dynamic game is used, where in each stage there exists another dynamic game, one for between ISP and EROs and another for between ISP and SUs, to model the market more practically. Despite this complex game structure, we provide a closed-form equilibrium analysis, which gives an insight of how much economic benefits are obtained by ISP, SUs, and EROs under what conditions.**

I. Introduction

Gartner predicts that about 21 billion "things" across industry sections will be connected to the network by 2020 [1]. We are also witnessing a growing number of things at the edge providing and sharing compute, storage, sensing, and network resources, which are expected to become more individually-owned and managed in the future. Example applications include mobile cloud computing [2], [3], and contents (e.g., sensing and video streaming) provisioning [4], [5]. This trend has begun to attract much attention in industry as well as academia, which is often referred to as *fog computing and networking* (simply fog computing throughout this paper). This paradigm shift can be understood as following the philosophy of sharing economy in the area of computing and networking, which has already experienced a huge success in other business sectors, e.g., Uber, Lyft, Airbnb.

In this paper, we aim at analyzing a market of fog computing, consisting of (i) end Service Users (SU), (ii) Service Provider (SP), (iii) Infrastructure Provider (InP), and (iv) Edge Resource Owners (ERO). SUs are end users who are ready to enjoy edge-based applications, e.g., IoT applications.

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[0]This work was supported by Institute for Information & communications Technology Promotion(IITP) grant funded by the Korea government(MSIT) (No. B0717-18-0034, Versatile Network System Architecture for Multi-dimensional Diversity)

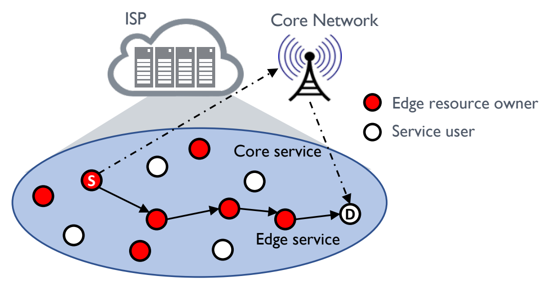


Fig. 1. Fog Computing System.

EROs are mostly individuals or companies with a small-scale communication and sensor infrastructures, who own edge resources or fog clouds. Especially, individual edge resource owners, just like an Uber driver in the car sharing business, partially or even entirely share and sell their resources to an InP, if satisfactory incentives are provided. SPs create diverse edge-based applications that attract SUs as OTT (Over-The-Top) providers. Logically, they do not necessarily own the resources of fog clouds or edge devices, but rent them. Thus, they often make a contract with InPs that manage the edge resources. InPs own and manage the large-scale infrastructure of communications, sensors, and clouds but may also rely on individual EROs to expand their infrastructures, by running a fog network orchestration platform, e.g., [6]. We particularly consider the case when SPs and InPs behave as one business unit, called ISP (Infrastructure and Service Provider), which is highly likely to be run by current mobile network operators (MNOs). The MNOs such as AT&T in US, and KT, SKT, LGU+ in Korea have actually started to run such joint SP/InP business with focus on IoT applications, e.g., [7].

To model a market of fog computing, we consider a single ISP and many SUs and EROs, where we formulate an ISP-platformed two-stage dynamic game. In the first stage, ISP and EROs play a dynamic sequential game, which determines how actively EROs participate in the expansion of the fog infrastructure by being paid a certain amount of incentives. In the second stage, ISP and SUs also play a dynamic sequential game, which finally determines the revenue and the utility of SUs. Thus, two dynamic games are mediated by ISP, which we call *ISP-platformed two-stage dynamic game*. We appropriately model the heterogeneity of SUs and EROs in terms of willingness to pay, and quality of the shared edge resources. Despite a significantly complex game structure mainly due to their embeddings, we successfully provide the closed-form of the prices and the economic benefits (e.g., revenues and utilities) at the equilibrium, that quantifies which factors have how much impact on the fog ecosystem under what conditions.

Fog computing, which brings computing, storage and networking closer to end users for better Quality of Service (QoS) is being actively discussed in three major groups, i.e., Cloudlet [8], Mobile Edge Computing [9] and Open Fog Consortium [10]. Also, in the literature, there are some proposals for the design and implementation of Fog computing, e.g., [6], [11], [12], stressing to allow third-party service providers to create new types of services by exploiting individual resources at edge. The authors in [13] point out that due to the limited resources of InPs, it is crucial to provide a mechanism to incentivize the EROs, and one of example ecosystems among EROs, SUs, and ISPs is discussed in [6], as modeled in this paper. Related to this goal, there are an array of prior works in the area of User Centric Network (UCN), where two categories are studied: *autonomous* and *network-assisted* UCN. In autonomous UCNs such as OpenGarden [14], no platform provider is involved, and EROs autonomously form a network and share their resources with other EROs or users based on a pre-defined incentive mechanism. Thus, only the interaction between EROs and SUs is required, as studied in [15], [16].

From the perspective of modeling and analysis, our work is close to what has been done in network-assisted UCNs, where incentivization is usually led by ISPs. Karma [17] and FON [18] are the commercialized services of this form. In [19], [20], a two-stage Stackelberg game is modeled between an ISP as the leader and EROs as followers. In [19], the authors focus on the interaction between the ISP and the hosts (i.e., EROs in this paper), where SUs are modeled in a highly abstract manner. In [20], an optimal incentive is studied, where there are *two competitive or cooperative* ISPs in the market. They model the utility of users which is identical for both EROs and SUs, with a focus only on maximizing users' total utility, rather than taking account into individual ones. The contribution of this paper is two-folds: (i) ISP is placed as a mediator between EROs and SUs by treating them as the same level of economic players, thereby two sequential games (one between ISP and EROs and another between ISP and SUs) are necessary to be embedded in a larger dynamic game, and (ii) we explicitly model a major feature inherent to (user-oriented) Fog computing, which is the impact of ERO participation on the quality of services to SUs.

II. Model and Game Formulation

A. System Model

ISP, SUs and EROs. We consider a single ISP playing the role of both InP and SP as mentioned earlier, that provides a service to SUs and leases the edge resources from EROs. We assume that there are N number of SUs, and bN number of EROs, where $b > 0$. SUs pay the service fee to ISP, when they subscribe to the service from the ISP, and EROs decide to share their edge resource, contributing to an expansion of ISP's infrastructure, if incentives are appropriately provided.

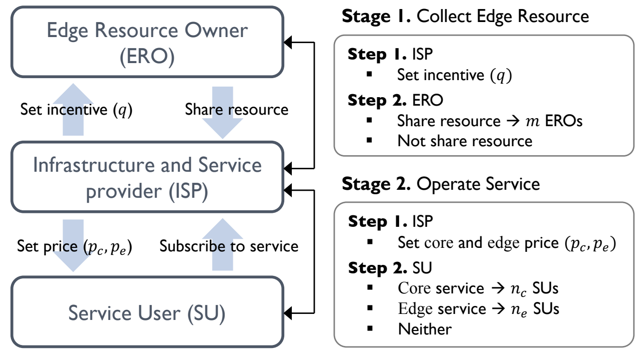


Fig. 2. Game formulation: ISP-platformed two-stage dynamic game.

Services. The ISP provides the networking service with two types: (i) core and (ii) edge. The core service corresponds to the case when SUs use a cellular mobile internet service such as LTE and the edge service refer to the one that SUs use only nearby edge resources. Thus, SUs can choose one service of core, edge, or none. The ISP sets the service prices p_c and p_e for core and edge services, respectively. To provide the edge service, the ISP needs to lease the edge resources from EROs by paying the incentive q. Depending on q, each ERO makes decision on whether to share its resource or not.

Quality of* core *and* edge *services. We denote by α_c the quality of core service, which is assumed to be homogeneous SUs' preferences across applications, so that SUs' utility purely depends on α_c, once they subscribe to core. We let α_e be the quality of edge service, to be modeled as:

$$\alpha_e(m, a) = \alpha_c \left(1 - (am + 1)^{-1}\right), \tag{1}$$

where $m \leq bN$ is the number of EROs which decide to share their resources, and the parameter constant a models how quickly the quality of edge service increases with m, relying on the underlying network topology and specific connectivity technology. In our model, the quality of edge service is worse than that of core, which typically holds in practice due to the difference in the resource availability and stability between core and edge. Thus, α_e depends on how many EROs decide to share their resources, being modeled as a concave, e.g., an increasing function with respect to m to reflect the effect of diminishing returns. Moreover, the value of m is also induced by our game model that will be introduced in the following subsection.

B. Game Formulation

We aim at understanding how ISP, SUs and EROs interplay for providing and consuming the edge services under the competitive relationship between them and analyzing their behaviors at the equilibrium. To this end, we now present a ISP-platformed two-stage dynamic game in which the three types of players interplay sequentially. As illustrated in Fig. 2, ISP initially leads a sequential game to collect the resources from EROs at Stage I and subsequently does to operate two-types of services to SUs at Stage II. By doing so, the ISP determines its strategies p_e, p_c, q to maximize its revenue denoted by π (see (2)), while EROs (or SUs) individually decide their own strategy $y \in \mathcal{S}_{\texttt{ERO}}$ (or $x \in \mathcal{S}_{\texttt{SU}}$) to maximize individual utility denoted by $u^{\texttt{ERO}}$ (or $u^{\texttt{SU}}$) where $\mathcal{S}_{\texttt{ERO}}$ (or $\mathcal{S}_{\texttt{SU}}$) denotes the strategy set of EROs (or SUs). We now present more details of our ISP-platformed two-stage dynamic game.

ISP-platformed Two-stage Dynamic Game

Stage I: How to collect edge resources? ISP vs. EROs. ISP first sets the incentive q as a leader, then each ERO having willingness-to-share θ selects its service among $\mathcal{S}_{\texttt{ERO}} \triangleq \{s, n\}$, where '$s$' and '$n$' correspond to sharing and non-sharing, respectively.

Step 1. ISP (Leader): $\quad q^\star = \arg\max_{q\in[0,1]} \pi(q, y, p_c, p_e, x),$

Step 2. ERO (Follower): $\quad y^\star(\theta) = \arg\max_{y\in\mathcal{S}_{\texttt{ERO}}} u^{\texttt{ERO}}(q, y; \theta),$

where the strategies p_c, p_e, x are given by Stage II.

Stage II: How to operate networking services? ISP vs. SUs. ISP first decides the service prices p_c and p_e, each SU with willingness-to-pay γ chooses which service to subscribe to out of $\mathcal{S}_{\texttt{SU}} \triangleq \{c, e, n\}$, where we use the '$c$', '$e$' and '$n$' to refer a SU's selection of core, edge, or neither.

Step 1. ISP (Leader): $\quad (p_c^\star, p_e^\star) = \arg\max_{(p_c,p_e)} \pi(q, y, p_c, p_e, x),$

Step 2. SU (Follower): $\quad x^\star(\gamma) = \arg\max_{x\in\mathcal{S}_{\texttt{SU}}} u^{\texttt{SU}}(p_c, p_e, x; \gamma),$

where the strategies q, y are given by Stage I.

We now present how the payoff functions in the above game are modeled in what follows:

Utility of ERO. An ERO's utility is determined by the resource sharing cost, incentive to share, and its willingness to share. To model this, we consider the following utility function:

$$u^{\texttt{ERO}}(q, y; \theta) = \begin{cases} q - \theta q_0, & \text{if } y = \text{'}s\text{'}, \\ 0 & \text{if } y = \text{'}n\text{'}, \end{cases}$$

where $y \in \mathcal{S}_{\texttt{ERO}}$ is the strategy of ERO, q_0 denotes ERO's cost for resource sharing and θ represents the willingness to share of an ERO that is assumed to be a uniformly random value over the interval $[0, 1]$. For example, for a given cost q_0, an ERO with a smaller θ has less sensitivity on cost (or more willingness to share) its resource than the one with a larger θ.

Utility of SU. A SU's utility would be affected by various factors, of which we focus on the following primary factors: service fees (p_e, p_c) and QoSes (α_e, α_c) of core and edge services. To model this, we consider the following utility function:

$$u^{\texttt{SU}}(p_e, p_c, x; \gamma) = \begin{cases} \gamma\alpha_e - p_e, & \text{if } x = \text{'}e\text{'}, \\ \gamma\alpha_c - p_c, & \text{if } x = \text{'}c\text{'}, \\ 0, & \text{if } x = \text{'}n\text{'}, \end{cases}$$

where $x \in \mathcal{S}_{\texttt{SU}}$ is the strategy of SU and γ is the heterogeneous willingness to pay of each SU, which is uniformly distributed at random in $[0, 1]$. For a given QoS, a SU with higher γ has more willingness to pay than the one with smaller γ.

Revenue of ISP. The revenue of ISP consists of an income from providing core and edge services and an expenditure on operating core network and leasing edge resources. Recall that core serves higher quality than edge, we now further assume that the price per unit quality of core is higher than that of edge, i.e., core is a high-end service satisfying $\frac{p_c}{\alpha_c} > \frac{p_e}{\alpha_e}$. Then, the net-revenue of ISP is given by:

$$\pi(\cdot) = N\int_0^1 \Big\{ (p_c - p_0)\cdot \mathbf{1}_{\{\gamma>\min(\gamma_{ce},1)\}} + p_e \cdot \mathbf{1}_{\{\gamma_{en}<\gamma\le\min(\gamma_{ce},1)\}} \Big\} d\gamma - bN\int_0^1 q\cdot\mathbf{1}_{\{\theta<\theta_0\}} d\theta, \quad (2)$$

where we denote by p_0 the cost for providing core service.

The terms γ_{ce} and γ_{en} are *the marginal willingness to pay* of SUs, which are induced by strategy decisions of SUs[1]. In other words, a SU with γ_{ce} (or γ_{en}) has the same utility when choosing strategies c and e (or e and n). Similarly, we denote by θ_0 *the marginal willingness to share*, i.e., $q - \theta_0 q_0 = 0$. ISP gains by core from the highly consuming SUs with $\gamma > \min(\gamma_{ce}, 1)$ as well as does by edge from the less consumable SUs with $\gamma_{en} < \gamma \le \min(\gamma_{ce}, 1)$. Similarly, ISP spends on leasing edge resources from the EROs who is willing to share with $\theta < \theta_0$, where the marginal willingness to share is denoted by θ_0, i.e., $q - \theta_0 q_0 = 0$. Finally, the incomes and the expenditures are, naturally, proportional to the number of SUs and EROs, N and bN, respectively.

Remark. Recall that the quality of edge is a function of the number of resource-sharing EROs, denoted by m. From (2), we can induce m as:

$$m(\cdot) = bN\int_0^1 \mathbf{1}_{\{\theta<\theta_0\}}\ d\theta.$$

In other words, m is the number of EROs who have smaller sensitivity on cost (or higher willingness to share) than θ_0.

III. Fog-computing UCN Market Analysis: Service Operation and Resource Aggregation

In this section, we provide the equilibrium analysis for the ISP-platformed two-stage dynamic game described in the previous section. We adopt the classical backward induction to find the subgame perfect equilibrium of our sequential game. Our sequential analysis in turn gives us the answers on how to operate `core` and `edge` services between ISP and SUs in Stage II, as well as how to collect the edge resources between ISP and EROs in Stage I.

A. How to Operate core *and* edge*: ISP vs. SUs in Stage II*

We first focus on the interaction between ISP and SUs in Stage II where ISP sets the service fees, p_c, p_e, and each SU determines which service she subscribes to. Assuming that the ISP successfully leases edge resources by giving incentive (q) to EROs in Stage I, then the QoS of edge service is

[1]Always $\gamma_{ce} \ge \gamma_{en}$ holds, which is proved in our technical report [21].

determined, so that SUs make decisions based on the given price and QoSes.

Consider the following condition C1:

$$\texttt{C1}: \quad q < \frac{q_0(\alpha_c - p_0)}{abp_0N}, \tag{3}$$

which corresponds to the case when the core service becomes more efficient in the sense of cost and quality. Depending on whether C1 holds or not, we divide the cases into two regimes: R1. *core-preferred regime* when C1 holds, and R2. *edge-dominant regime*, otherwise. Proposition 3.1 states when each SU chooses which services under what conditions.

Proposition 3.1 (Step 2 of Stage II): Then, the strategy of a SU with the willingness-to-pay γ at the equilibrium under each regime is given as follows:

R1. *Core-preferred regime.*

$$x^\star(\gamma) = \begin{cases} c, & \text{if } \gamma > \frac{p_c - p_e}{\alpha_c - \alpha_e}, \\ e, & \text{if } \frac{p_e}{\alpha_e} < \gamma \le \frac{p_c - p_e}{\alpha_c - \alpha_e}. \\ n, & \text{otherwise.} \end{cases} \tag{4}$$

R2. *Edge-dominant regime.*

$$x^\star(\gamma) = \begin{cases} e, & \text{if } \gamma > \frac{p_e}{\alpha_e}, \\ n, & \text{otherwise.} \end{cases} \tag{5}$$

Due to space limitation, we present the proof in our technical report [21]. When core service is efficient in terms of cost in the core-preferred regime, the ISP provides both core and edge services. In this case, the marginal willingness to pay γ_{ce} and γ_{en} are determined by $\frac{p_c - p_e}{\alpha_c - \alpha_e}$ and $\frac{p_e}{\alpha_e}$, respectively, which in turn determines which SUs choose core, edge, or no service. In the edge-dominant regime, core service is not provided by the ISP, and only edge or no service is chosen by SUs. Note that there is no regime where ISP only provides core service, because providing edge service always make additional revenues (or utility) to of both ISP and SUs.

Now, following the optimal decisions by SUs at Step 2 of Stage II, the ISP chooses the prices of edge and core to maximize its revenue, as stated in Proposition 3.2.

Proposition 3.2 (Step 1 of Stage II): The ISP sets the equilibrium prices $p_c^\star$ and $p_e^\star$ as follows:

$$p_c^\star = \frac{p_0 + \alpha_c}{2}, \quad p_e^\star = \frac{\alpha_e}{2} = \frac{\alpha_c abNq}{2(abNq + q_0)}, \tag{6}$$

where we have the quality of edge as $\alpha_e = \frac{\alpha_c abNq}{(abNq + q_0)}$.

The proof is presented in our technical report [21]. The ISP is the leader in Stage II and thus it knows how SUs act. Thus, if the QoS of edge service is given, ISP determines the price to maximize its revenue by predicting SUs' action. Since the QoS of core service is independent of the amount of leased edge resource, the price for core, p_c, is not a function of the quality of edge service. Thus, by controlling only the price of edge service p_e, ISP maximizes its revenue. As the incentive q given to the EROs grows, the equilibrium price of edge service increases. It is natural that higher incentive makes better QoS of edge service and the more SUs intend to subscribe to edge service, so that increasing the price can help in increasing the revenue.

B. How to Collect Edge Resource: ISP vs. EROs in Stage I

In this subsection, we analyze the interactions between the ISP and EROs in Stage I. In this stage, ISP leases edge resource from EROs by giving incentive q. Thus, our central interest is of how much the edge resource from EROs is collected, and in conjunction with the results in Stage II, what is the revenue of ISP at the equilibrium of the entire game.

In the backward induction of the global two-stage dynamic game, the ISP predicts SUs' equilibrium behaviors depending on its price decision in Stage II and its revenue according to its decision of incentive in Stage I. Thus, the ISP plays with the best responses for the behaviors of EROs. By analyzing the behaviors of EROs and ISP, we find the equilibrium incentives. The equilibrium strategy of an ERO with willingness-to-share θ is easily given as follows:

$$y^\star(\theta) = \begin{cases} s, & \text{if } \theta < \frac{q}{q_0}, \\ n, & \text{otherwise,} \end{cases} \tag{7}$$

where the marginal willingness to share θ_0 is $\theta_0 = \frac{q}{q_0}$. Theorem 3.1 presents the incentive to EROs, the prices for SUs, and the revenue of ISP under each regime at the equilibrium.

Theorem 3.1 (Equilibrium of fog-computing UCN market): The equilibrium prices of edge and core services $p_e^\star$, $p_c^\star$, the equilibrium incentive $q^\star$, and the equilibrium revenue $\pi^\star$, which exist in either R1 or R2, are as follows:

R1. *Core-preferred regime.*

$$p_c^\star = \frac{p_0 + \alpha_c}{2}, \quad p_e^\star = \frac{\alpha_e}{2} = \frac{\alpha_c abNq^\star}{2(abNq^\star + q_0)},$$
$$q^\star = \min\big(\frac{p_0^2 aN}{8\alpha_c}, q_0\big),$$
$$\pi^\star = \min\big(\frac{p_0^4 a^2 bN^3}{64\alpha_c^2 q_0}, \frac{p_0^2 abN^2}{4\alpha_c} - bNq_0\big) + N\frac{(p_0 - \alpha_c)^2}{4\alpha_c}.$$

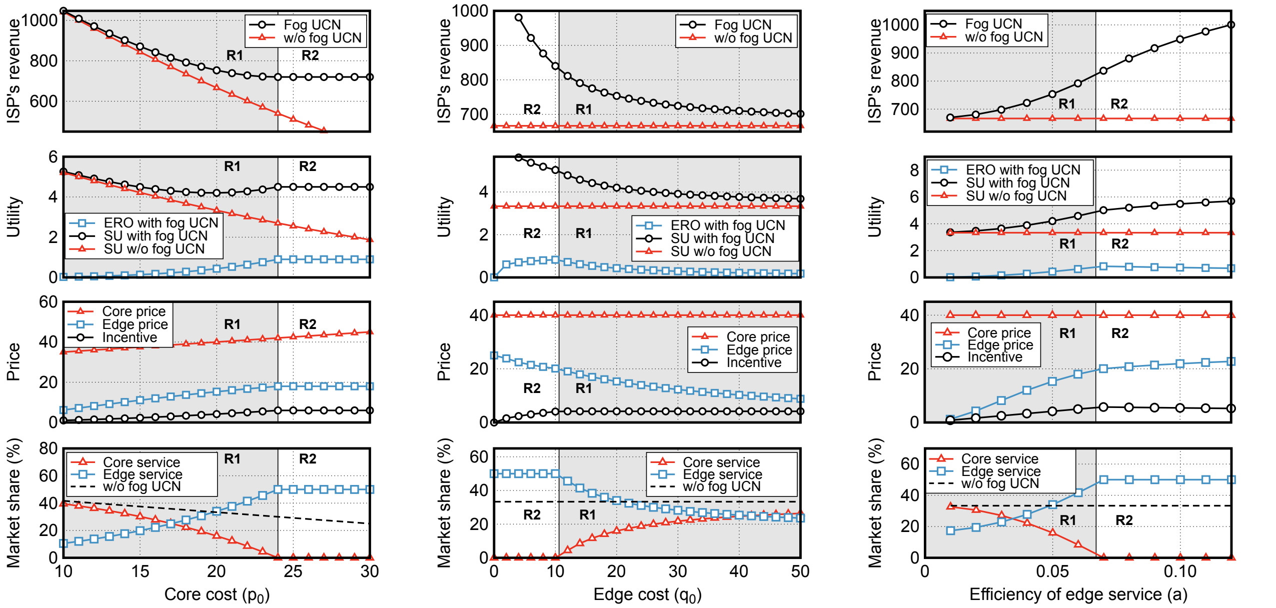
R2. *Edge-dominant regime.*

$$p_c^\star \in \big[\frac{p_0 + \alpha_c}{2}, \infty\big), \quad p_e^\star = \frac{\alpha_e}{2} = \frac{\alpha_c abNq^\star}{2(abNq^\star + q_0)},$$
$$q^\star = \min\big(\widetilde{q}, q_0\big),$$
$$\pi^\star = \frac{\alpha_c abq^\star N^2}{4(abq^\star N + q_0)} - \frac{bNq^{\star 2}}{q_0},$$

where $\widetilde{q}$ is a unique real solution of the following cubic equation:

$$8q(abNq + q_0)^2 = q_0^2 \alpha_c aN.$$

We present the full proof in our technical report [21]. The ISP can provide service in two configurations: (i) both core and edge services simultaneously in R1, and (ii) only edge service in R2. Recall that we introduced the equilibrium prices $p_c^\star$ and $p_e^\star$ in Proposition 3.2. Now we have the equilibrium



(a) Impact of core cost (p_0) (b) Impact of edge cost (q_0) (c) Impact of efficiency of edge network (a)

Fig. 3. ISP's revenue, SU's total utility and market share of core and edge service for varying core cost (p_0) and edge cost (q_0).

incentive $q^\star$ by Stage I analysis. For R2, the closed form of $q^\star$ is omitted due to the space limitation thus is provided in our technical report [21]. From the equilibrium prices and incentive, we readily drive the revenue of ISP at the equilibrium under each regime.

In R1, the equilibrium incentive $q^\star$ is closely related to the cost p_0 and quality of core service α_c. As core service becomes more fascinating i.e., higher quality and lower cost, the incentive tends to decrease as well as ISP provides core service more aggressively. However, in R2, ISP's decision of the incentive does not depend on core's cost but on the maximum incentive. ISP's revenue decreases as the cost p_0 for providing core service increases. As the strength of using edge service grows, i.e., low cost q_0 or high efficiency a, the revenue of ISP also grows up. We provide the numerical examples to illustrate the impacts of the cost of core service p_0, the cost of edge service q_0, and the efficiency of edge service a on the equilibrium behaviors as Fig. 3 in Section IV.

C. Utilities of SUs and EROs

When we apply the equilibrium prices and incentives under each regime in Theorem 3.1 to SUs' and EROs' utilities, the following Proposition 3.3 is obtained.

Proposition 3.3 (Average utilities of SUs and EROs): At the equilibrium in Theorem 3.1, the average utilities of SUs and EROs denoted by $\bar{u}^{\texttt{SU}}$ and $\bar{u}^{\texttt{ERO}}$ under each regime are as follows:

R1. *Core-preferred regime.*

$$\bar{u}^{\texttt{SU}} = \frac{\alpha_c^2 abN + (\alpha_c - p_0 abN - p_0)^2}{8\alpha_c(abN+1)}, \quad \bar{u}^{\texttt{ERO}} = \frac{q^{\star 2}}{2q_0}.$$

R2. *Edge-dominant regime.*

$$\bar{u}^{\texttt{SU}} = \frac{\alpha_c abN}{8(abN+1)}, \quad \bar{u}^{\texttt{ERO}} = \frac{q^{\star 2}}{2q_0}.$$

The proof is presented in our technical report [21]. Similarly to the ISP's revenue, the average utility of SUs increases in the efficiency of edge service a and decreases in the cost of edge service q_0. Especially, in R1, the average utility of SUs is a convex function with respect to the cost of core service p_0, it implies that there may exist a trade-off between the equilibrium prices and the quality of services when increasing core cost. Moreover, the average utility of EROs increases in the core cost and the edge efficiency of edge. We show the numerical examples to illustrate the average utilities of SUs and EROs according to the costs q_0, p_0, and the edge efficiency a as Fig. 3 in Section IV.

IV. Numerical Result

In this section, we provide numerical result to further illustrate the analytical result in Section III. We first show the impact of edge service in fog computing, and see the impact of environmental parameters which affect the equilibrium of players. In all numerical analysis, we set the number of edge device as $N = 100$ and environmental parameter $a = 0.05$ and $b = 1$ which implies that if 50 EROs out of 100 share their resource, then QoS of edge service is 70% of that of core service. We used the core cost $p_0 = \$25$ and the edge cost $q_0 = \$25^2$, and assume that the QoS of core service (α_c) is \$60 which is higher than p_0.

A. Impact of Fog-computing UCN on ISP's Revenue, SUs' and EROs' Utilities, and Market Shares

As the emergence of fog-computing UCN, ISP can provide edge service. In order to show the impact of edge service, we compare the case where ISP provides both edge and core services with the other case where ISP provides networking service without fog-computing UCN.

[2]We get p_0 from AT&T's monthly data plan of IoT cellular service [22] and q_0 from incentive policy of Karma [17] where ERO can earn 25\$ if it shares resources to 25 number of users.

Observation 1. edge *service improves ISP's revenue by 33% and SUs utility by 26%.* The graphs in first low of Fig. 3 show the revenue of ISP. In fog-computing UCN, ISP provides SUs with core and edge service simultaneously, but for comparison, we also draw the ISP's revenue when ISP provides only either core or edge service. In all graphs, ISP's revenue in fog-computing UCN case overwhelms other cases and this verifies the result of Theorem 3.1. Additionally, although ISP tries to maximize its own revenue, the SUs' average utility increases as shown in graphs in second row of Fig. 3. In our environmental parameter setting, the revenue of ISP increases 33% and SU's total utility increase 26% comparing with the case where there is no edge service. Thus, we can conclude that edge service is always helpful to both ISP and SUs.

Observation 2. edge *service reduces the use of core network.* Bottom graphs in Fig. 3 include two information: *(i) the market share between* core *and* edge *services in fog-computing UCN*, and *(ii) that of* core *service when there is no* edge *service (dotted line in graphs).* The number of SUs subscribing to core service in *(i)* is always smaller than that in *(ii)*. It is because SUs whose willingness to pay is relatively low, prefer to subscribing to edge service with lower price despite its lower QoS. Thus, providing edge service can reduce the traffic which go through core network.

B. Impact of Costs and Edge's Efficiency on SUs' Service Selections and ISP's Pricing Decisions

In this section, we study the impact of environmental parameters such as core cost p_0, edge cost q_0, and the efficiency of edge service a on ISP's operation regime, and EROs' and SU's selection of strategies in fog computing market between core and edge services.

*Observation 3. Conditions for Regimes (*R1 *and* R2*).* ISP's action is different according to the regime as described in Proposition 3.1, and the regime is determined by environmental parameters such as p_0, q_0 and a. In Fig. 3, shaded area means regime R1 and the other means regime R2. As edge resource becomes efficient (i.e., a, p_0 increase or q_0 decreases), ISP prefers to providing edge service, and it finally falls in regime R2 and provides only edge service.

Observation 4. ISP's selection of price and incentive. The graphs in third row of Fig. 3 shows ISP's selection of price and incentive which changes for varying environmental parameter. First, as the core cost (p_0) grows, ISP increases the core price (p_c) and reduces the number of SUs subscribing to core service which causes large cost. On the other hand, core price is independent of parameters related to edge service (i.e., q_0, a). Similarly, ISP increases edge price (p_e) as the edge service becomes relatively efficient comparing to core service (i.e., a, p_0 increase or q_0 decreases). Finally, the incentive (q) behaves similar to edge price in regime R1, however, in regime R2 ISP decreases incentive as edge service becomes efficient. In this case, edge service is more efficient than core so that SUs select to subscribe to edge service even if the QoS of edge service is low.

V. CONCLUSION

In an IoT era, it is expected a huge number of edge devices to be deployed by individuals in the near future. Definitely, the next step is to design how to share widely distributed and individually owned edge resources to realize economics of Fog computing. In this paper, we model/analyze an emerging edge resource market, especially for Fog computing UCN, consisting of ISP, EROs, and SUs. In this ecosystem, ISP which provides a platform of fog computing, behaves as a mediator to lease edge resources from EROs and provide services to SUs. By modeling this market as ISP-platformed two-stage dynamic game in which the three types of players interact sequentially, we prove the existence of a Fog computing feasibility region, where Fog computing UCN increases ISP's revenue as well as utility of EROs and SUs.

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