Competitive Analysis of Data Sponsoring and Edge Caching for Mobile Video Streaming

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ABSTRACT

Cellular data sponsoring (CDS) is a traditional data sponsor scheme widely used in cellular video delivery networks, where content providers (CPs) bear the cellular data downloading cost for mobile video users (MUs), so as to attract more MUs and achieve higher revenue (e.g., via more attached advertisements). Edge caching sponsoring (ECS) is a novel data sponsor scheme recently introduced in the emerging 5G network, where CPs cache popular video contents on the edge network in advance and deliver them to local MUs directly. Thus, it can not only achieve the benefits of CDS (i.e., attracting more MUs and achieving higher revenue), but also reduce the congestion of backhaul network. In this work, we will perform a competitive analysis of CDS and ECS for mobile video streaming. Specifically, we consider a mobile video delivery network with two CPs who adopt CDS and ECS, respectively. MUs can choose one or neither of these two sponsor schemes (from the corresponding CPs) for his video content requests. We formulate the interaction of CPs and MUs as a two-stage Stackelberg game, where CPs act as *leaders* determining the efforts of their adopted sponsor schemes in the first stage, and MUs act as *followers* choosing the best sponsor schemes for their content requests in the second stage. We analyze the sub-game perfect equilibrium systematically for both cooperative and competitive scenarios (depending on whether two CPs cooperate or compete with each other). Numerical results show that in the competitive scenario, the joint sponsor of ECS and CDS can increase the total MU payoff by 36% $\sim$ 140%, comparing with that with only one sponsor scheme. Moreover, the CPs can benefit more from ECS than from CDS when the revenue is higher.

KEYWORDS

Data Sponsoring, Edge Caching, Content Delivery Networks

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1 INTRODUCTION

1.1 Background and Motivations

Nowadays, we are witnessing the explosive growth of global mobile video traffic. According to Cisco[1], mobile video traffic accounts for a majority of the total mobile traffic (e.g., 60% in 2016). Due to the fast increase of video traffic, the increased data cost is becoming one of the major concerns for mobile users to consume videos. This brings additional challenge for CPs, as they need to consider not only the quality improvement of their video services as before, but also the cost reduction for the users who request their services.

One effective way to reduce user cost is *data sponsoring* [1, 2], which has been employed by many CPs worldwide. The key idea of data sponsoring is to allow CPs to subsidize the user's cost of mobile video data, hence attract more mobile video users and traffic. Data sponsoring creates a win-win situation for mobile users and CPs, that is, mobile users benefit from the free access of video contents, and CPs benefit from the increased video users and traffic[2]. In this case, the video data is delivered via cellular networks, and hence the data cost mainly contains the cellular data cost. As a real-world example, AT&T announced its sponsored data program in January 2014, in which AT&T allows advertisers (CPs) to sponsor mobile data to entice more users to watch their advertisements.

In the forthcoming 5G cellular networks, *edge caching* is emerging as a promising technique to deliver videos with lower cost and higher quality [3–6]. The key idea is to cache the popular video contents on edge networks (e.g., femtocell base stations [4] and WiFi access points [5]) in advance and deliver the cached contents to video users directly via local connections (e.g., WiFi direct). Obviously, with edge caching, mobile users can obtain video contents without involving the cellular data cost. In this sense, edge caching can be viewed as a new sponsorship scheme for mobile users. Edge caching has the potential of alleviating backbone network burden, providing high-quality video, and reducing content delivery cost. As an example, Xunlei [5], one of the largest content delivery networks (CDNs) in China, has deployed WiFi APs with large storage capacity to deliver video contents for mobile users.

[1]Cisco visual networking index: Global mobile data traffic forecast update 20160201 white paper
[2]For example, they can sell more built-in advertisements.

Many existing works have studied the cellular data sponsoring [1, 2] and the edge caching [5, 6] separately. Some works investigate how to jointly use the two sponsor schemes [7–9]. However, the competition between CPs using CDS and ECS has not been extensively discussed. In this work, we aim to understand how the newly introduced ECS will affect the traditional CDS under the competitive scenario, and how the co-existence of CDS and ECS will change the user behavior and the whole data market.

1.2 Solution and Contributions

To concentrate on the mutual interaction of CDS and ECS, we consider a simple model with two representative CPs: one (called ECS-CP) offers ECS to mobile users, and the other (called CDS-CP) offers CDS to mobile users. As in many existing literature [5, 6], we assume that the cellular network is available in the whole area, while the edge network is only available in part of the area due to the limited distance of short-range transmission. Moreover, we consider a general scenario with multiple users, where users are *heterogeneous* in terms of individual valuation and data price. Given the sponsoring schemes provided by the CPs, mobile users decide whether and which sponsoring scheme they will choose, according to their valuation and data price. Note that when a user chooses neither sponsoring scheme, the content will be delivered to the user through cellular network and the user will bear the cellular data cost as in traditional cellular networks. Fig. 1 illustrates such a system model with different sponsor schemes, where red and green users download video contents via the CDS and ECS, respectively, while grey users download video contents without sponsoring.

On one hand, by covering the data cost for users with either ECS or CDS, the CPs can attract more video users and traffic, and hence achieve certain *revenue gain* (e.g., via build-in advertisements). On the other hand, when providing sponsoring for users, the CPs need to pay some *efforts* for covering the cellular data cost (in CDS) or caching the video contents on edge network (in ECS), hence lead to certain *revenue loss*. The CPs can decide their sponsor efforts in CDS and ECS, respectively: the CDS-CP decides the percentage of the sponsored content to the total content; the ECS-CP decides whether to cache a content in a location, and further the video quality and priority to deliver the cached content.

Clearly, a higher effort for a particular sponsoring scheme can attract more users to choose it (hence bring more revenue gain for the CP), but will also introduce more revenue loss to the CP to offer the sponsoring. Thus, the CPs need to determine the efforts for each sponsoring scheme carefully to balance the revenue gain and loss. Note that the *value-added content* in sponsored content may reduce the user experience for the video content, hence users can refuse the sponsoring and pay the corresponding data downloading cost by themselves as usual. Therefore, there is an inherit competition between these two sponsor schemes. To capture the competitive interaction among CPs, we consider CPs compete and each determines the sponsor effort independently to maximize its own profit. Based on the above model, we will investigate how the CDS and ECS jointly affect the MUs' behaviors and benefits as well as the CPs' benefits under the competitive scenario.

We analyze the problem by using game theory. In particular, we formulate the interaction among CPs and MUs as a two-stage Stackelberg game [10], with CPs as leaders and mobile users as followers. In Stage I, the CPs decide their respective sponsor efforts. A large sponsor effort can potentially attract more user requests for the CP. In Stage II, given the sponsor efforts of CPs, each mobile user chooses the proper sponsor scheme for each of his request. We investigate the *competitive scenario*, where CPs compete for the video users (e.g., Netflix and Hulu). We will analyze the *Sub-game Perfect Equilibrium (SPE) [10]* of the proposed game systematically.

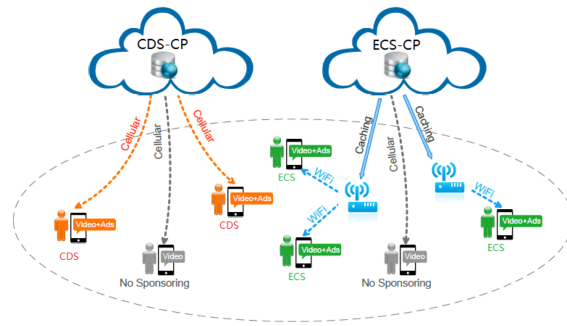


Figure 1: System Model.

In summary, the key contributions of this work are as follows.

- *Novel Data Sponsor Model:* To our best knowledge, we are the first to study the competition between CDS and ECS CPs. Our model captures many important features of practical systems, such as the request heterogeneity, the user QoE and the network condition.
- *The Competitive Model:* We formulate the problem as a two-stage game, and analyze the game equilibrium comprehensively. Specifically, we analyze the existence and uniqueness of equilibrium in the competitive scenario.
- *Experiments and Insights:* We conduct extensive experiments to evaluate the system performance. The experiment results show that with a lower caching cost, the ECS can achieve a larger payoff for the CP.

2 SYSTEM MODEL

We consider such a video content delivery network where CPs offer video contents to a pool of mobile network users with both CDS and ECS are enabled.

2.1 Network Model

Considering a practical scenario, we assume that the mobile users move randomly among a few locations. We refer to a *location* as the signal coverage region of an edge caching device, which can provide ECS. We define the set of users as $\mathcal{N} = \{1, 2, ..., N\}$, and the set of locations as $\mathcal{L} = \{1, 2, ..., L\}$. We assume all the locations are covered by the cellular network, which can provide CDS. Users may appear in a location and request a content. We notice the fact that the same video is often available from many CPs, which applies particularly to popular videos [11] . Namely, there is competition among different CPs as they may provide the same video contents to the same cluster of users.

In order to get some insights into the problem, we investigate the scenario with one particular content cached in one edge device in the following analysis. We simply normalize the content size as 1 to get some insight into the problem. We focus on the cooperative/competitive interactions between the two sponsor schemes. Note that the analysis can be generalized to the multi-location-multi-content scenario by conducting multiple parallel analysis.

2.2 CDS Model (Cellular Sponsoring)

In CDS, the CP can choose to cover part or all of the content data cost for the user. Specifically, the CP can decide the percentage of sponsored cost to total cost of the content $x \in [0, x_{\max}]$, where $x_{\max} > 1$. When $x < 1$, the CP sponsors x percentage of data cost. Note that $x > 1$ means that the CP sponsors the total user cost and compensates the user with additional revenue. This especially happens when a CP plans to promote a new video to users. Once the cellular sponsored request is initiated by users, the content will be delivered with extra *value-added* contents, e.g., advertisements. The value-added content will bring additional revenue for the CP, and we define the one-time sponsor revenue for the CP as w. We assume that the extra advertisement length is fixed like in [2] , hence making the CP's revenue a constant. Hence, the CP can potentially bring more users and gain more revenue via CDS. From the user's perspective, once the request is sponsored via CDS, the user's data cost is discounted by x. As the irrelevance of value-added content have negative effect on user experience, some users may refuse to accept the sponsoring.

2.3 ECS Model (Caching Sponsoring)

In ECS, the CP will decide to cache which contents in each location in advance. Furthermore, the CP needs to decide the caching effort of the content in each location. In the model, we denote the caching effort as $y \in [0, y_{\max}]$, with $y_{max} > 1$, indicating the comprehensive video quality, delivery priority and reserved wireless link capacity [6] in the edge caching network. We assume that the baseline content caching cost is C_c. Hence the cost of the CP for caching a video content with caching effort y is $y \cdot C_c$.

Once the content is cached, it will be kept for a relatively long time period before getting replaced (*e.g.,* daily replacement [12]). During the time period, users in this location can access the cached content. If the ECS is accepted by the user, the CP will obtain the revenue w brought by the value-added content. Besides the value-added content, the network handover and caching effort will also affect the user experience [2], and we will provide the detailed analysis in Section 2.4. As edge cache potentially has negative effect on the user experience, users may choose to refuse the ECS.

2.4 User Model

Users move among locations and request contents. When a content is requested, it will incur data cost for the user, and bring utility for the user. As the data cost and user utility are in different units, we introduce normalized values $v, c \in [0, 1]$ to represent the user request, i.e., (v, c) (referred to as the *type* of request), where v denotes the normalized user utility to watch the content and c denotes the normalized data cost to initiate the request.

Each user has a normalized data price c, because in reality users' data costs differ from each other due to varied data prices. User utility on watching a specific video (denoted as v) refers to the user's subjective valuation on the content, which based on the user preference, urgency, and video popularity. The evaluation of v is a well-studied topic [13], hence is out of the scope of this paper. Different requests bear different costs and utilities, which are independent and identically distributed (i.i.d) according to probability distribution functions $f(c)$ and $g(v)$, respectively. To obtain closed form results, in the rest of the analysis, we assume uniform distribution for c and v, i.e., $f(c) = 1$, $\forall c \in [0, 1]$, and $g(v) = 1$, $\forall v \in [0, 1]$. However, our analysis method applies for arbitrary distribution functions $f(c)$ and $g(v)$.

In this work, we focus on the *symmetric equilibrium* where users with the same *type* will always make the same decision.There are four possible choices for the user $s \in \{N, I, C, E\}$:

- N: the request is not initiated (hence incur no cost),
- I: the user refuses sponsor schemes and downloads data via cellular link as normal.
- C: the user accepts the CDS from the CP (hence download data via cellular links with reduced cost),
- E: the user accepts the ECS from the CP (hence download data via local link without cellular costs).

The payoff of each user is the achieved utility minus the incurred cost. For convenience, we denote the payoff of a type-(v, c) request under decision s as $u_{(v,c)}(s)$. The user's objective is to make a proper decision to maximize his payoff. Next we define the user payoff function:

1) Not Initiated Request: The user does not initiate the content request, hence cannot access the content. We define the user payoff in this case as zero:

$$u_{(v,c)}(N) = 0. \tag{1}$$

2) Initiated Request without Sponsoring: The user refuses the sponsoring schemes, and requests the content with his own data quota as normal. Hence, the user payoff is:

$$u_{(v,c)}(I) = v - c. \tag{2}$$

3) Initiated Request with CDS: The user accepts the CDS when requesting the content. In this case, the user will bear the experience degrade induced by the attached value-added contents, and meanwhile get a part of the data cost covered. Thus, users will be affected by two variables set by the CP: the ads length fraction to the video length α, and the percentage of sponsored content x. We assume the length of the extra advertisement attached in sponsored content is s_a. Thus, we can derive α as follows:

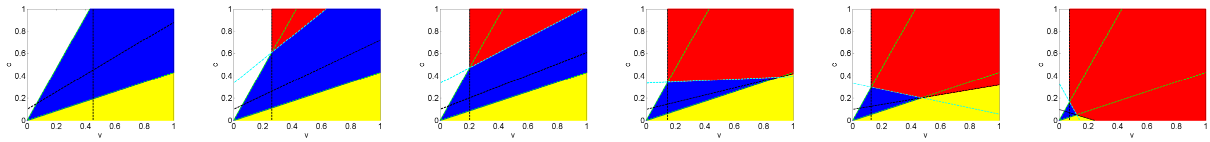
$$\alpha = \frac{1}{s_a + 1}. \tag{3}$$

We assume that the ads length embedded in each content is the same, i.e., α is a constant, and the only decision variable for the CP is the sponsored percentage x. Hence, the user payoff is defined as:

$$u_{(v,c)}(C) = \alpha v - (1 - x)c. \tag{4}$$

4) Initiated Request with ECS: The user accepts the ECS when requesting the content. The user will bear the experience degrade induced by both the attached ads and video quality degrade brought up by cache, and meanwhile have the whole content sponsored via caching network. Hence, the user payoff is formulated as:

$$u_{(v,c)}(E) = \alpha h(y) \cdot v - c_0, \tag{5}$$



(a) $x = 0.7$, $y = 0.1$ (b) $x = 0.7$, $y = 0.3$ (c) $x = 0.7$, $y = 0.5$ (d) $x = 0.7$, $y = 0.95$ (e) $x = 0.7$, $y = 1.25$ (f) $x = 0.7$, $y = 4$

Figure 2: Illustration of user decision. (White: not initiated, Yellow: no sponsoring, Blue: CDS, Red: ECS.)

where c_0 is the network handover cost from the default cellular network to the edge cache network, and $h(y)$ is a *video quality function*, which reflects the network condition and caching effort in edge cache network. $h(y)$ is a monotonically increasing function reflecting the influence of caching effort y on user experience. We adopt a common example of *video quality function*:

$$h(y) = \frac{1}{1-\gamma} \cdot y^{1-\gamma}, \tag{6}$$

where $0 < \gamma < 1$ [2], which is an monotone increasing concave function. This implies that user satisfaction increases with the delivery priority and the marginal payoff decreases.

Summarizing the above analysis, we reformulate the user payoffs under different selections as an equivalent formulation:

$$u_{(v,c)}(s) = \begin{cases} 0, & s = N \\ v - c, & s = I \\ \alpha v - (1-x)c, & s = C \\ \alpha h(y)v - c_0, & s = E \end{cases} \tag{7}$$

3 COMPETITIVE CPS

In this section, we will provide the analysis of the model where CDS and ECS coexist, and this can be formulated as a two-stage decision problem. In Stage I, the CPs decide their sponsor efforts by setting (x, y), respectively. In Stage II, the users will make their decisions based on the CPs' decisions. We consider the problem in the competitive scenario: the CPs compete with each other to achieve their own optimal payoffs, respectively. In this scenario, the CPs need to consider the decisions of the competitor and users to achieve the his own maximal payoff. Next, we will analyze the problem by backward induction.

3.1 Users' Best Decision in Stage II

Now we study the users' best decision game in Stage II, given the CPs' decisions (x, y) in Stage I. The user decisions can be summarized as follows:

A type-(v, c) user request will initiate without sponsoring, if and only if

$$u_{(v,c)}(I) > \max\{u_{(v,c)}(C), u_{(v,c)}(E), 0\}, \tag{8}$$

A type-(v, c) user request will accept the CDS, if and only if

$$u_{(v,c)}(C) > \max\{u_{(v,c)}(I), u_{(v,c)}(E), 0\}, \tag{9}$$

A type-(v, c) user request will accept the ECS, if and only if

$$u_{(v,c)}(E) \geq \max\{u_{(v,c)}(I), u_{(v,c)}(C), 0\}, \tag{10}$$

We plot the user distribution under different sponsor decisions in Fig. 2. We define $\eta = \frac{v}{c}$ as the *utility-to-cost* ratio, and further notice that a user request with very large η tends to refuse the data sponsoring, and we call this *utility sensitive* request. A user request with very small η tends to accept the data sponsoring, and we call this *cost sensitive* request. Moreover, *cost sensitive* requests with large c tends to accept ECS, and requests with small c tends to accept CDS. Intuitively, *utility sensitive* requests care much about utilities even incurring a high cost, and *cost sensitive* requests means that without reducing the cost through sponsoring, the content does not deserve watching.

We introduce the following function to characterize the user selection between CDS and ECS: $l_0(v) = v$, $l_1(v) = \frac{\alpha}{1-x}v$, $l_2(v) = \frac{1-\alpha}{x}v$, $l_3(v) = \frac{c_0}{\alpha h(y)}$, $l_4(v) = (1 - \alpha h(y))v + c_0$ and $l_5(v) = \frac{1-h(y)}{1-x}\alpha v + \frac{c_0}{1-x}$. With the introduced functions, we can derive the user decision distribution. Specifically, we have the following lemma illustrating the user decision distribution:

Lemma 1. (1) *A user request (v, c) will choose initiation without sponsoring only when $0 < v < l_3(v)$ and $[\max(l_0(v), l_2(v)]_0^1 < c < 1$.*

(2) *A user request (v, c) will choose initiation with CDS only when $[\min(l_2(v), l_5(v))]_0^1 < c < [\min(l_1(v), l_5(v))]_0^1$.*

(3) *A user request (v, c) will choose initiation with ECS only when $l_3(v) < v < 1$ and $[\max(l_4(v), l_5(v))]_0^1 < c < 1$.*

The illustration of user decision distribution is depicted in Fig. 2(a) ~ Fig. 2(f). We set $x = 0.7$ and multiple values of y in a increasing sequence. When $y = 0.1$, we find in Fig. 2(a) that no user chooses ECS because the delivery priority is too low. With the increase of y, we find that some non-initiated and cellular sponsor requests will choose ECS when y is small. When y is large enough, it starts to attract some former initiated without sponsoring requests. We also find that $l_5(v)$ is determined by the intersections of $l_1(v)$ and $l_3(v)$, and $l_2(v)$ and $l_4(v)$. Intuitively, $l_5(v)$ serves as the rule for requests choosing CDS and ECS. As we can derive the user distribution under fixed CP's decision, we have the following theorem:

Theorem 1. *There exists and only exists one equilibrium in the user decision game in Stage II.*

Based on the above analysis, we can compute the total user payoff under (x, y). The total user payoff U_n can be represented as the sum of user payoffs including *Initiated without Sponsoring*, *Cellular Sponsored*, and *Cache Sponsored*. Thus, U_n can be computed as follows:

$$\begin{aligned} U_n = N \cdot [&\int_0^{l_3(v)} \int_{[\max(l_0(v), l_2(v)]_0^1}^1 (v - c) f(c) dc g(v) dv + \\ &\int_0^1 \int_{[\min(l_2(v), l_5(v))]_0^1}^{[\min(l_1(v), l_5(v))]_0^1} (\alpha v - c(1-x)) f(c) dc g(v) dv + \\ &\int_{l_3(v)}^1 \int_{[\max(l_4(v), l_5(v))]_0^1}^1 (\alpha h(y) v - c_0) f(c) dc g(v) dv] \end{aligned} \tag{11}$$

3.2 CP's Utility

Now we study the utilities of CDS-CP and ECS-CP, respectively.

The CPs' payoffs are coupled with each other by making their sponsoring decisions. CDS-CP's payoff can be computed by summing up the payoffs of all the user requests accepting cellular sponsoring. The CP payoff can be represented as:

$$U_{\text{CDS-CP}} = N\cdot\int_0^1 \int_{[\min(l_2(v),l_5(v))]_0^1}^{[\min(l_1(v),l_5(v))]_0^1} (w-c\cdot x)g(v)dvf(c)dc \quad (12)$$

Similarly, we can sum up the payoffs of all the user requests accepting caching sponsoring to obtain ECS-CP's payoff. The CP payoff $U_{\text{ECS-CP}}$ can be represented as:

$$U_{\text{ECS-CP}} = N\cdot\int_{l_3(v)}^1 \int_{[\max(l_4(v),l_5(v))]_0^1}^{1} wg(v)dvf(c)dc - C_c y \quad (13)$$

We notice that both $U_{\text{CDS-CP}}$ and $U_{\text{ECS-CP}}$ are functions of x and y, hence the CPs' decisions are coupled with each other and determined by the user decision in Stage II. Next we introduce cooperative and competitive CPs.

3.3 Competitive CPs' Best Decision in Stage I

In the competitive scenario, the CPs are the players, and they decide the sponsoring efforts x and y. Given ECS-CP's decision y, the CDS-CP can compute the best x to maximize its own payoff. We denote the best decision as a function of y, *i.e.,* $C(y)$. We have

$$C(y) \in arg \max_{x\in[0,x_{\max}]} U_{\text{CDS-CP}}(x,y). \quad (14)$$

Similarly, we denote the ECS-CP's best decision as a function of x, *i.e.,* $\mathcal{E}(x)$. We have

$$\mathcal{E}(x) \in arg \max_{y\in[0,y_{\max}]} U_{\text{ECS-CP}}(x,y). \quad (15)$$

Theorem 2. *When the CPs' decisions are mutual best responses, we achieve the Nash Equilibrium of the game, denoted by (x^*, y^*), which satisfies*

$$\mathcal{E}(C(y^*)) = y^*, \quad C(\mathcal{E}(x^*)) = x^*$$

Next Theorem characterizes the condition for the existence and uniqueness of the CP best decision equilibrium.[3]

Theorem 3. *There exists a unique pure CP decision equilibrium (x^*, y^*) if we can find a region $[x_{\min}, x_{\min}+a], a > 0$ with $0 \le x_{\min} < x_{\min}+a \le x_{\max}$, and another region $[y_{\min}, y_{\min}+a]$ with $0 \le y_{\min} < y_{\min}+a \le y_{\max}$, where $x^* \in [x_{\min}, x_{\min}+a]$ and $y^* \in [y_{\min}, y_{\min}+a]$, if the following conditions are satisfied:*

(1) *$C(y)$ and $\mathcal{E}(x)$ are monotonically increasing in $[y_{\min}, y_{\min}+a]$ and $[x_{\min}, x_{\min}+a]$, respectively.*
(2) *$C(\mathcal{E}(x_{\min})) \ge x_{\min}$ and $C(\mathcal{E}(x_{\min}+a)) \le x_{\min}+a$ exist, or $\mathcal{E}(C(y_{\min})) \ge y_{\min}$ and $\mathcal{E}(C(y_{\min}+a)) \le y_{\min}+a$ exist.*
(3) *$\mathcal{E}(x) - x$ and $C(y) - y$ are strictly monotonically decreasing in $[x_{\min}, x_{\min}+a]$ and $[y_{\min}, y_{\min}+a]$, respectively.*

[3]Even for a convex game, the uniqueness of the NE is not guaranteed. Hence we cannot employ the convexity of $U_{\text{CDS-CP}}$ and $U_{\text{ECS-CP}}$ to prove the uniqueness in our game.

In most of our simulations, we can find regions satisfying condition 1), conditions 2) and 3), however, they are not always satisfied in simulations. However, we note that conditions 1) – 3) are sufficient but not necessary conditions, and a CP decision equilibrium may exist even if these conditions are not satisfied.

4 NUMERICAL RESULTS

We perform numerical study in this section. First, we introduce two benchmark schemes for comparison: the *sole CDS* scheme, in which only the CDS is utilized, and the *sole ECS*, in which only the ECS is utilized. In our numerical studies, we consider one cellular tower covering a region, and edge devices are distributed within the coverage of the cellular tower. In this way, the CDS and ECS coexist within the cellular tower range. We conduct the experiment with simulated data, and choose the default system parameters as follows. We choose $\alpha = 0.7$, which is the discount of extra advertisement on user QoE, $w = 0.5$, which is the per request revenue of the CP, $c_0 = 0.15$, which is the normalized user cost selecting ECS, $\gamma = 0.5$, which is the parameter of *video quality function.* We further assume that the total user request number $N = 10000$, and the cost for edge caching $C_c = 4500$. Next, we investigate the two-stage game jointly, and derive the optimal decision of competitive CPs.

4.1 Competitive CPs' Best Decisions

First, we investigate the CPs' optimal decision under competitive scenario. We first look into the single CP's optimal decision under coexistence of CDS and ECS. We present the optimal CDS-CP's decision $x^*(y)$ in Fig. 3(a), and the optimal ECS-CP's decision $y^*(x)$ in Fig. 3(b). We notice that $x^*(y)$ is monotone increasing with y and $y^*(x)$ is monotone increasing with x, the intuitive explanation may be that the CP has to pay more sponsor effort to attract more users, when his competitor invests in more effort. After we derive $x^*(y)$ and $y^*(x)$, we can further compute the intersection of $x^*(y)$ and $y^*(x)$ in Fig. 3(c), and the intersection is the CPs' optimal decisions under the competitive scenario: $(x^* = 0.87, y^* = 1.85)$.

Next, we investigate the MUs' payoff under the competitive scenario. Fig. 4 shows the MUs' payoff under best competitive scenario, with sole CDS and ECS as baselines. We notice that MUs' payoff under competitive scenario is always larger than the baselines. That is, The competition between CPs will always benefit the MUs as the CPs will increase the sponsor effort to attract MUs. The payoff under competitive scenario outperforms sole sponsor baselines by $36\% \sim 140\%$. The MUs' payoff under ECS is larger than under CDS as the amplification effect of edge caching.

4.2 Impacts of Important Parameters

Next, we will illustrate how the parameters affect the CPs' decisions and payoffs.

4.2.1 Impact of sponsor revenue w. As presented in Fig. 5(a), with larger sponsor revenue w, both CP and user payoff are monotonically increasing in the competitive scenario. The CP's payoff benefit from the increase of the sponsor revenue directly. As the larger revenue incentives the CPs to pay more sponsor efforts, more user requests will be sponsored, and hence the sum user payoff will increase. Figure. 5(b) indicates that ECS-CP's payoff and CDS-CP's payoff monotonically increases with w. However, ECS-CP's payoff

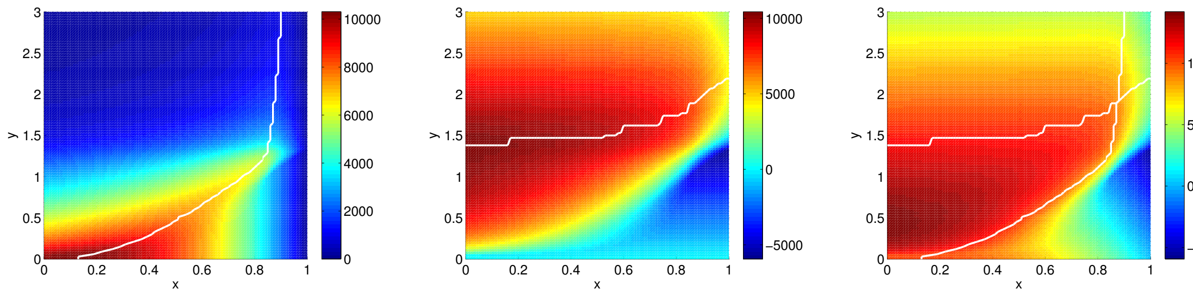


Figure 3: (a) CDS-CP's payoff and best response, (b) ECS-CP's payoff and best response, (c) Illustration of sum CP payoff and best CP decision under cooperative and competitive scenarios.

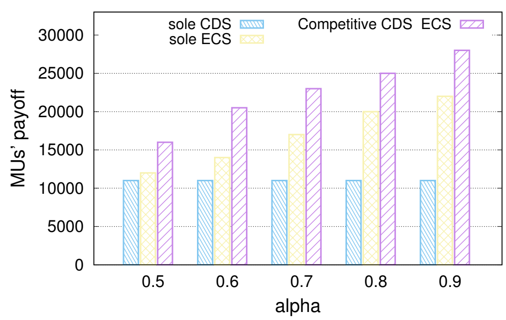


Figure 4: MUs' payoff versus α.

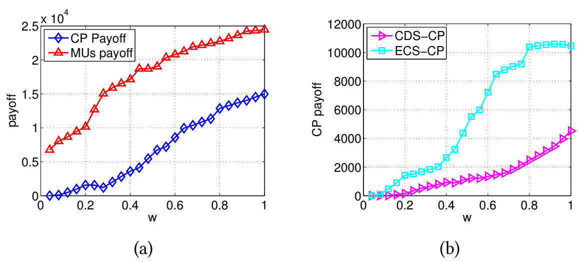


Figure 5: (a) sum CP payoff and user payoff versus sponsor revenue w, (b) CDS-CP and ECS-CP payoffs versus sponsor revenue w.

increases much faster than the CDS-CP's payoff. We conclude that ECS-CP is *w-sensitive*, as the payoff of ECS-CP increases dramatically with w. Thus, for the contents with very high CP revenue, the novel ECS is a better selection for sponsorship.

5 CONCLUSION

In this work, we analyze the sponsor market where CDS-CP and ECS-CP compete with each other. Then, we studied the sponsoring decision and user choice via a two-stage game. We studied the CPs' best sponsor decision under the competitive scenario and propose the sufficient conditions for the uniqueness of the equilibrium in Stage I. In the experiment results, we obtain that the competition of CPs can benefit the MUs' payoff by 36% $\sim$ 140% increase.

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