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Incentivizing Mobile Video Users With Data Sponsoring and Edge Caching

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ABSTRACT Recently, edge caching has emerged as a new data sponsoring scheme, where the devices on the edge network, e.g., 4G/5G base stations, cache video contents and directly delivery them to mobile video users. Such caching schemes have significantly decreased the backhaul congestion, reduce the delivery latency, thus attract more mobile video users and monetize a huge number of videos. In this paper, we consider a hybrid caching schemes system, which combines edge cache sponsoring (ECS) and traditional cellular data sponsoring (CDS), where the content providers display advertisements to mitigate the cellular data downloading expense and provide attractive contents for mobile video users. In the system, we investigate the cooperative scenario and the competitive scenario between the two sponsoring schemes, and a mobile video user can select one scheme or neither of them for the requests of a video. In the first scenario, we focus on achieving the maximal total benefit of content providers by optimizing CDS and ECS schemes together. In the second scenario, we separately optimize ECS and CDS schemes and maximize the benefits of corresponding content providers. To illustrate the effectiveness of the two scenarios, we formulate the system as a two-stage game: 1) in the first stage, content providers (i.e., leaders) choose the sponsor effort in sponsor schemes (cooperatively or competitively); 2) in the second stage, mobile video users (i.e., followers) select their sponsor preferences. We conduct numerical results to explore the sub-game perfect equilibrium and find that the joint utilization of the two sponsor schemes can benefit the mobile video users, i.e., when ECS and CDS compete with each other, MUs can benefit 36% $\sim$ 140% more than the case where there exists only one sponsor scheme. While when CPs cooperate with each other, their total payoff is maximized, the mobile video users' payoff also increases. Moreover, we find that ECS can benefit the content providers more than CDS when sponsor revenue is high, and this indicates that ECS is a promising sponsor scheme for the high-value contents.

INDEX TERMS Data sponsoring, edge caching, content delivery networks.

I. INTRODUCTION

The proliferation of high-performance mobile devices and the development of communication technologies (e.g., 4G/5G) have shifted the patterns of today's Internet traffic. According to the newest Internet whitepaper [1] published by Cisco in 2019, the data traffic of mobile devices is expected to grow sevenfold between 2017 and 2022, at a Compound Annual Growth Rate (CAGR) of about 46% during the forecast period, reaching 77.5 exabytes per month by 2022. In particular, mobile video traffic has become the most important contributor in mobile data traffic, accounting for 79% by 2022. The increasing mobile data traffic also brings the following challenges from the perspective of mobile video content providers (CPs): 1) the delivery of mobile video contents relies on a large number of Content Delivery Networks (CDNs), such increasing mobile video traffic will bring the pressure of delivery capacity and high probability

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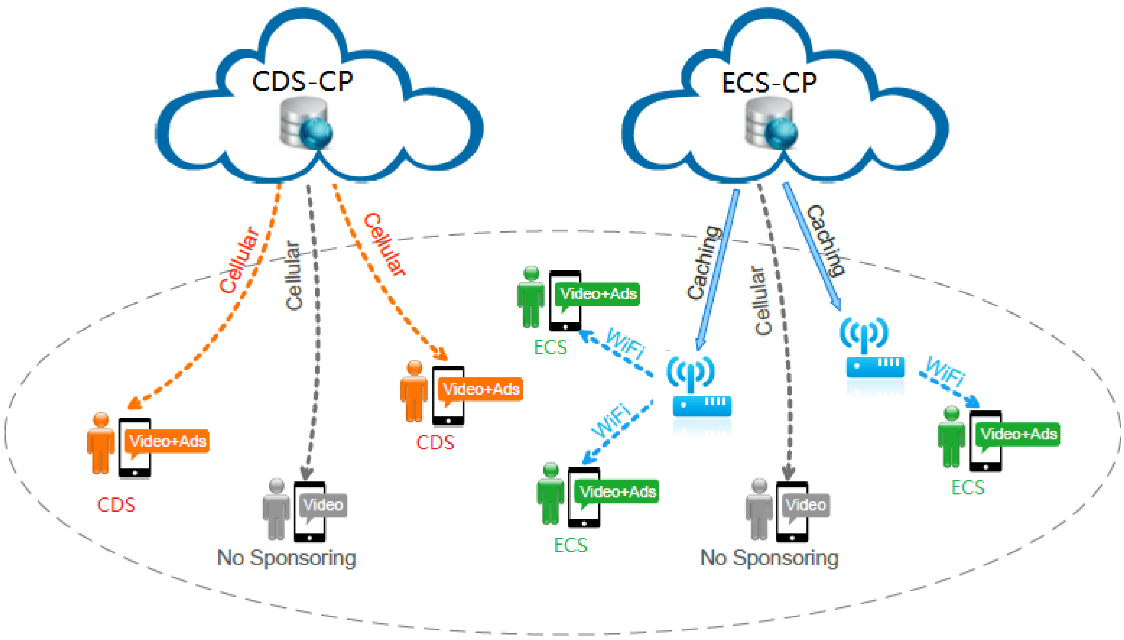


FIGURE 1. System model.

of traffic congestion; 2) CPs who chase more revenue must continuously propose incentive strategies improve their competition and attract new mobile video users (MUs).

As a traditional and widely-adopted incentive scheme, Cellular Data Sponsoring (CDS) [2]–[5] allows CPs to cooperate with the service providers of cellular networks and provide "Free Video Traffic" plan for MUs, improving MU's retention ratio, attracting new MUs, and achieving higher revenue (e.g., performing several advertisements before a video starts), and MUs can enjoy free cellular traffic when watching video contents in CDS. This scheme achieves a win-win situation for CPs and MUs. Note that the ISP can also achieve more revenue because of these CP's payment for cellular traffic [2], but it is not the main focus in this paper. Taking an AT&T's plan as an example, AT&T have provided a cellular data sponsor plan to the U.S. mobile data market in January 2014 [6], where the CPs can cover the cost of data traffic for MUs.

Edge caching [7]–[11] has been seen as one of the main supporting technologies in 5G wireless networks. The key idea of edge caching is to host popular video contents in the edge networks (e.g., cell stations and smart WiFi routers with storage capacity), and directly deliver the contents cached at the edge to the MUs via a wireless network, e.g., femto-caching [9], and WiFi-aided caching [12]. The amplification effect of cache can potentially alleviate the backhaul traffic. In China, several downloading service providers have purchased users' spare bandwidth and storage capacities to assist content delivery among neighbour users. Specifically, such emerging edge caching networks can be employed by CPs for sponsoring, and CPs can cache contents on the edge network and sponsor nearby MUs because the downloading cost in the edge caching network is negligible compared to cellular data cost.

Today, some existing works have studied CDS [2]–[5] and edge caching [7]–[11] separately. However, as far as we know, all of these works did not consider the two sponsor schemes jointly. In the future 5G network, it will become a trend that Cache-enabled Small Base Station (CSBS), e.g., femtocell and WiFi access point, will be widely considered as the communication infrastructure of edge cache network. Macro Base Station (MBS), which is the communication infrastructure of cellular network will coexist with CSBS to deliver contents for users, hence CDS and edge cache sponsoring (ECS) will be jointly enabled for the CPs [13]. It is essential to study the case where CDS and ECS coexist as user incentive mechanisms. In this work, we will study the scenarios that CDS and ECS compete and cooperate in the sponsor market, investigate the CPs' and MUs' benefits together, explore MU's behaviors.

In this paper, we consider a generic model, in which CPs provide Video on Demand (VoD) service to a large number of MUs, and users can choose sponsor schemes between CDS and ECS. Thus, two ways can be selected when delivering video contents to a target user: 1) via MBS, and 2) via CSBS, if the content is cached on a CSBS at an edge caching network and the user can be served by this CSBS. Note that the one video request can only be served by one network transmission scheme, as the video delivery is usually based on the HTTP/TCP protocols [14]. As shown in Fig. 1, a system model contains the two sponsor schemes, the video contents are delivered to the red, green, and grey users via the CDS scheme, the ECS scheme, and cellular network without any sponsoring, respectively. A content provider can choose CDS or ECS as his sponsor scheme. In CDS scheme, the content provider selects the sponsored content from all video contents. In ECS scheme, the content provider determines whether to cache a content on an edge network, and further the quality, priority and location of the cached content.

MUs can select a certain data sponsoring scheme according to their evaluation. If a mobile user chooses the CDS scheme, a part of traffic cost during video downloading is sponsored by the CP; otherwise, s/he pays the cost as usual. If a mobile user chooses the ECS scheme, s/he does not need to pay the traffic cost of video downloading, as the edge caching delivery cost is negligible. Thus, an inherent competition exists between the two schemes. To investigate the impacts of the two schemes, we explore both the cooperative scenario and the competitive scenario among different CPs. In the former case, CPs cooperate and jointly decide the sponsor efforts to maximize total profit. In the latter case, every CP determines the sponsor effort independently to maximize its own profit.

Based on this model, we will answer the following questions:

- How the CDS or ECS solely affects the MUs' behaviors/benefits and the CPs' benefits?
- How the CDS and ECS jointly affect the MUs' behaviors/benefits and the CPs' benefits under competitive and cooperative scenarios, respectively?
- How important parameters, *e.g.,* caching cost, sponsor revenue, affect the CP's benefit?

These questions are very important for understanding and optimizing the emerging sponsor schemes. To our knowledge, this is the first work that systematically investigates such a scenario where CDS and ECS coexist in the sponsor market.

We formulate the system as a two-stage game *Stackelberg game* [15]: 1) in the first stage, content providers (i.e., leaders) choose the sponsor effort in sponsor schemes (cooperatively or competitively); 2) in the second stage, mobile video users (i.e., followers) select their sponsor preferences. We investigate a *competitive scenario*, where CPs compete for the video users (e.g., Netflix and Hulu), and a *cooperative scenario*, where one CP employs both sponsor schemes or CPs establish an agreement to maximize the total payoff. We also study the *Sub-game Perfect Equilibrium (SPE)* in this game.

The key contributions of this work can be summarized as follows.

- We propose a novel data sponsor model with competition and cooperation scenarios between CDS and ECS. The model fully considers the issues in practice, such as, the MU's QoE, the networking status, and the heterogeneity of video requests.
- We formulate this model as a two-stage Stackelberg game and investigate the corresponding equilibrium (i.e., existence and uniqueness) comprehensively.
- We further evaluate the performance of the proposed model using extensive experiments. The results illustrate that the ECS scheme brings higher payoff for the CP under a lower caching cost.

The remainder of this paper can be summarized as follows. We provide the related work in Section II. In Section III, we conduct a measurement to get insight into the pattern of mobile video requests. We present the system model and problem formulation in Section IV. In Section V, we provide the pure CDS and ECS models, respectively. In Section VI, we illustrate the cooperative and competitive models of joint sponsoring in detail. We provide the numerical results in Section VII, and conclude this paper in Section VIII.

II. RELATED WORK

Data sponsoring has recently attracted much attention both from academia and industry because it potentially benefits ISPs, CPs, and users [2]–[4], [16], [17]. Existing works mainly study the data sponsoring scheme in a cellular networking scenario. Joe-Wong *et. al.* introduced a novel framework to investigate the sponsored data behaviours among heterogeneous end-users and CPs, and provide a new way to understand the mobile data market [2]. Paparas *et. al.* highlighted the challenges and opportunities when CPs sponsor users' requests for mobile data traffic. They further analyzed the impacts of fixed-quota data plan and proposed an online algorithm to maximize the corresponding revenue [3]. Zhang *et. al.* proposed a two-class service model and studied the impact of sponsored data plan on different types of users, including CPs, ISPs, and end users. They also observed that the unbalance of different CPs' revenue will be enlarged by the sponsored data plan [4]. Hande *et. al.* presented a quantitative framework to evaluate the benefits among the ISPs, CPs, and end-users' [18]. Some existing works also studied the interactions between the CP and the ISP [19]–[23].

These aforementioned works studied the data sponsor schemes from the perspective of optimizing traditional cellular networks, but did not cover the data sponsoring in edge caching schemes. Recent studies [7], [8], [10], [11], [24], [25] have shown the importance of edge caching, especially in mitigating the delivery pressure of CDNs, and optimizing the delivery cost in high-speed cellular networks, e.g., 4G/5G. In an edge caching scheme, edge nodes with large storage/bandwidth capacities are connected by low-rate backhaul links.

The edge cache node should be equipped with large storage capacity, high-rate delivery capacity and low-rate backhaul link. Wang *et. al.* adopted edge caching scheme to smooth data traffic, mitigate the unbalance of backhaul congestion, and achieve low-latency content delivery [8]. Bastug *et. al.* analyzed the effectiveness of edge caching at base stations and users' devices in 4G/5G networks, especially in reducing the backhaul traffic congestion [10]. Several recent works have implemented the prototypes of edge caching at different edge locations, such as, base stations [11], [24], [26], femtocell [9], small cell [25], [27], and Wi-Fi access points [28]. None of the edge cache related works consider achieving data sponsoring via edge cache network. As far as we know, we are

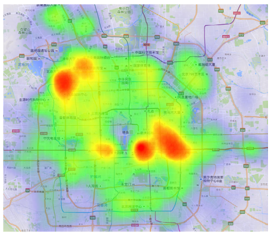


FIGURE 2. **The geographic distribution of APs.**

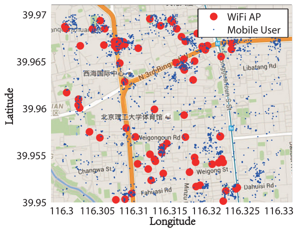


FIGURE 3. **The request & WiFi AP correlation.**

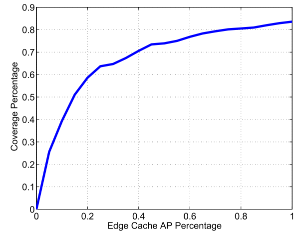


FIGURE 4. **The edge cache network coverage with AP number.**

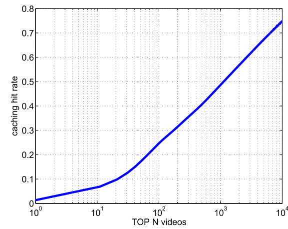


FIGURE 5. **The top N caching hit rate.**

the first to investigate sponsoring in edge caching network, along with the traditional cellular sponsoring. Our previous work has investigated the competitive model in edge cache networks [29], which can be considered as a sub-part of the models in this paper.

III. MEASUREMENT AND ANALYSIS

We first conduct a measurement based on a large-scale dataset to get insight into the pattern of mobile video request.

A. DATASET

1) MOBILE VIDEO REQUEST DATASET

In this paper, we study the requesting patterns of mobile videos using a dataset collected by one of the largest online video providers in China. The dataset consists of around three millions watching sessions (records) collected within two weeks in 2015-May in Beijing. Every record contains a mobile user ID, the requested video name, the timestamp of the request, the location of the user (in longitude and latitude), etc. There is a total of 0.19 millions mobile users and a total of 0.21 millions video contents in the dataset.

2) WIFI ACCESS POINT DATASET

We collect the information of WiFi APs via a mobile phone tool helping users connect to free WiFi with over 400 million mobile users in China. The dataset consists of the information (e.g., location) of more than 166,000 public WiFi APs in Beijing. Figure. 2 depicts the AP geographic distribution in Beijing. Each record contains the properties of one WiFi AP, including Basic Service Set Identifier (BSSID), location (in longitude and latitude), etc. Assuming the signal range of WiFi AP is $50m$, users will connect to the nearest AP within the signal range. Figure. 3 depicts an example of the mapping between user requests and WiFi APs.

B. DATA ANALYSIS

We provide the analysis of the above datasets to gain some insight. We first analyze the edge cache network coverage under different WiFi AP numbers, which is depicted in Fig. 4. Considering that only a part of routers are Smart Routers with caching capacity, we look into how the percentage of Smart Routers affect the edge caching coverage of video request. As the current Smart Routers percentage in Beijing is approximately 10%, we conclude that the current coverage of video requests is about 40%. We notice that when the percentage of Smart Routers approaches 80%, the edge cache network can cover 80% user requests within the city.

We further investigate the caching hit rate when caching local top N video contents. We consider a simple caching policy, i.e., caching the most popular video content locally. Fig. 5 shows that when caching local top 100 contents, the caching hit rate can reach approximately 25%. The wide coverage and high hit rate of the edge cache network enable the edge cache sponsoring for the CP.

Moreover, we notice in Fig. 2 that the WiFi AP distribution is highly skewed, which indicates the edge caching cannot be utilized in sparsely distributed regions. Fig. 3 illustrates that some user requests are not covered by any edge cache devices. That is, the edge cache network bears limitation from the coverage issue.

Based on the above analysis, we find the joint utilization of the cellular sponsoring and edge caching is promising. On one hand, we find that edge cache sponsoring is promising with more edge cache devices being deployed. Moreover, edge cache sponsoring shows its advantage to cellular sponsoring because of the reuse of popular video contents. On the other hand, due to the coverage and capacity limitations, it is necessary to use cellular sponsoring where the edge caching network is not available. In conclusion, it is efficient to employ both cellular data sponsoring and edge cache sponsoring for video content providers to attract more users.

IV. SYSTEM MODEL

In this paper, we consider the following video delivery scheme: content providers serve various video contents to a huge number of geo-distributed mobile users with both sponsor schemes enabled. The first type of sponsor scheme is CDS, in which the CP delivers the requested contents to the mobile users via the MBS, and sponsors part or all of the users' data costs (on the cellular links) in order to attract more video traffic. The second type of sponsor scheme is ECS, in which the CP can determine the caching strategy in the CSBS in advance and deliver the cached video contents to the nearby users through local wireless links directly (hence users do not need to pay the cellular data costs), with the advent of edge cache technology in the upcoming 5G network [7]–[10].

A. NETWORK MODEL

We first define the network model used in this paper, we consider a practical scenario where the MUs are able to randomly change their locations among several locations. Let a *location* denotes the signal coverage region of a CSBS, which can support the ECS scheme. Let $\mathcal{N} = \{1, 2, \ldots, N\}$ and $\mathcal{L} = \{1, 2, \ldots, L\}$ denote the set of users and the set of locations, respectively. Here, we assume that all the locations are within the coverage of an MBS, which can provide the CDS scheme. Mobile video content providers have their own content libraries, and some of the video contents can be provided by multiple CPs. In fact, if the same video content is usually cached and available in several resolutions and from various content providers, it can be considered as a popular video [30]. Thus, different CPs may provide the same popular videos to the same MUs, which also means that the competition exists among different CPs.

We consider a time slotted model, *i.e.,* each user appears in a location and request a content in a time slot. We denote $r = 0$ as the case that the user does not request a content at all, and $l = 0$ as the case that the user does not appear in a location covered by an edge cache server. The time structure can be represented as $\mathcal{T} = \{1, 2, \ldots, T\}$.

To reveal the important insights inside, we consider a scenario with one particular content cached in one CSBS in the following analysis. Let s denotes the content size, we assume that the CSBS is located in origin. We first analyze the CDS and the ECS respectively, and explore the cooperative interaction and the competitive interaction between the two schemes, which can be considered as a multi-location-multi-content scenario.

B. CDS MODEL (DATA SPONSORING)

In a CDS scheme, the CP can pay a part of or all of the traffic cost during video downloading period 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. Here, $x > 1$ 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 content 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. As a practical example, Youku [31], one of the largest video providers in China, adds the same video advertisement to the same video content. 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 has negative effect on user experience [32], [33], some users may refuse to accept the sponsoring.

C. 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 [34] and reserved wireless link capacity [10] 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 [35]). 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 IV-D. As edge cache potentially has negative effect on the user experience, users may choose to refuse the ECS.

D. USER MODEL

MUs change their locations and watch video contents at the same time. When a video content is requested, it will incur data cost for the user, and bring utility for the user. Because the data cost and user utility are in different units, let normalized values $v, c \in [0, 1]$ denote the status of a 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. Note that both v and c is relevant with the content size in reality, we simply normalize the content size $s_c = 1$ to get some insight into the problem.

Each user has a normalized data price $c \in [0, 1]$, because in reality users' data costs differ from each other due to varied data prices [36], in which user data price provided by AT&T may vary from \$4.5/GB to \$30/GB. User utility on watching a specific video (denoted as $v \in [0, 1]$) refers to the user's subjective valuation on the content, which is based on the user preference, urgency, and video popularity. The evaluation of v is a well-studied topic [37], hence is out of the scope of this paper. The practical example is that even for the same movie, different people may rate it with varied scores in Netflix [38]. 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 user requests with the same *type* will always make the same decision. There are in total four possible choices for the user $s \in \{N, I, C, E\}$, where

- N: the request is not initiated (hence incur no cost),
- I: the user refuses sponsor schemes and downloads data via a 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 a local link without cellular costs).

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

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, because it does not incur any cost or utility for the user:

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

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 can be 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:

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

where c_0 is the network handover cost from the default cellular network to the edge cache network [39], 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 [2]. 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], [4], [21], which is an monotone increasing concave function. This implies that user satisfaction increases with the delivery priority and the marginal payoff decreases.

For the simplicity of the analysis, we reformulate the above user payoffs as an equivalent formulation:

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

E. PROBLEM FORMULATION

Based on the above model, we formulate the problem as a two-stage decision problem. In stage I, the CP determines the sponsoring efforts in CDS and ECS simultaneously to maximize the total payoff. In stage II, given the CP's sponsoring efforts, MUs choose one or neither of these two sponsor schemes to maximize their payoffs.

V. PURE SPONSORING ANALYSIS

Before studying the coexisting sponsoring schemes, we provide the analysis of pure CDS and ECS, respectively, as baseline scenarios.

A. THE SCENARIO WITH PURE CDS

In the market with pure CDS, the user decision and the CP's decision are coupled. We analyze the problem as a two-stage game: in Stage I, the CP decides the sponsor percentage x, and in Stage II users decide whether to initiate a request and further whether to accept CDS. We analyze the game by backward induction.

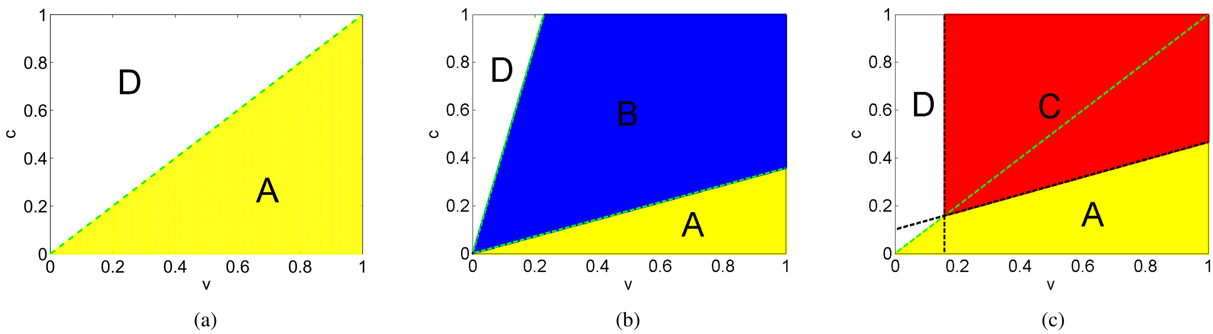


FIGURE 6. (a) User decision distribution without sponsoring, (b) User decision distribution with CDS, (c) User decision distribution with ECS. (A: Initiated without sponsoring, B: Initiated with CDS, C: Initiated with ECS, D: Not initiated request.)

The user decisions can be represented as $s \in \{N, I, C\}$. Hence, the user payoff is defined below:

$$u_{(v,c)}(s) = \begin{cases} 0, & s = N \\ v - c, & s = I \\ \alpha v - (1-x)c, & s = C \end{cases} \tag{8}$$

A type-(v, c) user will choose CDS, if and only if

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

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

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

We introduce the functions $l_1(v) = \frac{\alpha}{1-x}v$, and $l_2(v) = \frac{1-\alpha}{x}v$ to help analyze the user decision. We can characterize the existence of users accepting CDS in the following lemma.

Lemma 1: Only when $x > 1 - \alpha$, there exist users accepting CDS.

Proof: The user requests satisfying $l_2(v) < c < l_1(v)$ will accept CDS, so the condition that there exist users accepting CDS is $l_1(v) > l_2(v)$, i.e., $\frac{\alpha}{1-x} > \frac{1-\alpha}{x}$, thus $x > 1 - \alpha$.

This indicates that a small sponsor percentage cannot attract the user, as the attached advertisement harms the user QoE, which inspires that the CP with CDS has to decide a sponsor percentage above the threshold to attract users.

When $x \leq 1-\alpha$, the problem reduces to the scenario without sponsoring, and the user decision distribution is depicted in Fig. 6(a). We introduce $l_0(v) = v$ to analyze the user decision distribution under this case:

Lemma 2: A user request (v, c) will be initiated without sponsoring when $0 < c < l_0(v)$.

We can observe that without data sponsoring, a large part of user requests will not be initiated, and this decreases the potential user request number.

We can derive the user decision distribution depicted in Fig. 6(b), in which the yellow part is initiated requests without sponsoring, and the blue part is initiated requests with CDS. We compare Fig. 6(a) and Fig. 6(b) and notice that more user requests are initiated under CDS scenario. Hence we can conclude that CDS can motivate the users to initiate more requests, and may potentially attract more users for the CP.

With the knowledge of user decision distribution, the CP payoff $U_{\text{CDS-CP}}$ can be computed as:

$$\begin{aligned} &U_{\text{CDS-CP}} \\ &= N \int_0^1 \int_{l_2(v)}^{\lceil l_1(v) \rceil^1} (w - c \cdot x) dc dv \\ &= N\{\frac{(x+\alpha-1)(1-x)(3w\alpha-(2\alpha-1)x+\alpha-1)}{6x\alpha^3} \\ &\quad + (w - \frac{x}{2})\frac{\alpha+x-1}{\alpha} - \frac{w(1-\alpha)}{2x}[1-(\frac{1-x}{\alpha})^2] \\ &\quad + \frac{(1-\alpha)^2}{6x}[1-(\frac{1-x}{\alpha})^3]\} \end{aligned} \tag{11}$$

The optimal decision for the CP is to find $x^* \in [0, x_{\max}]$ that maximizes U_{CP}:

$$x^* = arg \max_{x \in [0, x_{\max}]} U_{\text{CDS-CP}}. \tag{12}$$

As $U_{\text{CDS-CP}}$ is a non-concave function and may have multiple extreme point, we utilize numerical methods to derive the optimal decision x^*. Although we find it difficult to derive the closed form x^* in this problem, we can derive the following lemma when the parameters satisfy $3w + \alpha \geq 1$:

Lemma 3: When $3w + \alpha \geq 1$ exists, $U''_{\text{CDS-CP}}(x) < 0, \quad \forall x \in [0, 1]$.

Then we can compute the x^* to achieve the maximal CP payoff by theorem 1.

Theorem 1 (The CP's Optimal Decision):

- If $U'_{\text{CDS-CP}}(1) \geq 0$, *i.e.*, $3w(1 + \alpha - \alpha^2) - \alpha^3 + 2\alpha^2 - 4\alpha - 2 \geq 0$, the best decision for the CP is $x^* = 1$.
- If $U'_{\text{CDS-CP}}(1 - \alpha) \leq 0$, *i.e.*, $2\alpha + 3w - 2 \leq 0$, the best decision for the CP is $x^* = 1 - \alpha$.
- On other conditions, the optimal $x^* \in (1-\alpha, 1)$, and we can employ numerical methods to solve x^*.

After deriving the CP's optimal decision, we can compute the total user payoff U_n, which includes the payoffs of requests initiated without sponsoring and with CDS.

Specifically, we can compute U_n as follows:

$$\begin{aligned}U_n &= N[\int_0^1\int_{l_2(v)}^{[l_1(v)]]^1}(\alpha v-(1-x^*)c)dcdv\\&+\int_0^1\int_0^{l_2(v)}(v-c)dcdv]=\frac{1-\alpha}{3x}-\frac{1}{6}(\frac{1-\alpha}{x})^2\\&+\frac{1}{3}(\frac{1-x}{\alpha})^3[\frac{\alpha^2}{2(1-x)}-\frac{\alpha(1-\alpha)}{x}+\frac{1-x}{2}(\frac{1-\alpha}{x})^2]\\&+\frac{1}{3}[-\frac{\alpha(1-\alpha)}{x}+\frac{1-x}{2}(\frac{1-\alpha}{x})^2](1-(\frac{1-x}{\alpha})^3)\\&+\frac{\alpha}{2}[1-(\frac{1-x}{\alpha})^2]-\frac{1-x}{2}(\frac{\alpha-1+x}{\alpha}).\end{aligned}\tag{13}$$

With the formulation of user payoff and CP payoff in (11) and (13), we can derive the payoffs under arbitrary distribution functions.

B. THE SCENARIO WITH PURE ECS

In the pure ECS scenario, the user decision set can be represented as $s \in \{N, I, E\}$. The corresponding user payoff is defined below:

$$u_{(v,c)}(s)=\begin{cases}0, & s=N\\ v-c, & s=I\\ \alpha h(y)v-c_0, & s=E\end{cases}\tag{14}$$

A type-(v, c) user will choose ECS, if and only if

$$u_{(v,c)}(E)\geq \max\{0, u_{(v,c)}(I)\},\tag{15}$$

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

$$u_{(v,c)}(I)\geq \max\{0, u_{(v,c)}(E)\},\tag{16}$$

Then we introduce $l_4(v) = (1-\alpha h(y))v + c_0$ and $l_3(v) = \frac{c_0}{\alpha h(y)}$ to analyze the user decision distribution. We characterize the condition of user requests initiated with ECS in the following lemma:

Lemma 4: A user request (v, c) will be initiated with ECS only when $v > l_3(v)$ and $[l_4(v)]_0^1 < c < 1$.

Proof: A user request will be initiated with ECS when $\alpha h(y)v - c_0 > 0$ and $\alpha h(y)v - c_0 > v - c$, hence $v > l_3(v)$ and $c > [l_4(v)]_0^1$.

The user decision distribution is depicted in Fig. 6(c). We notice that ECS can potentially attract more users for the CP than in no sponsoring scenario. Furthermore, ECS is attractive especially for the user requests with large cost as ECS can cover all the sponsor cost for users.

As we obtain the user requests accepting ECS, we can compute the CP payoff $U_{\text{ECS-CP}}$ as follows:

$$\begin{aligned}U_{\text{ECS-CP}} &= N\cdot\int_{l_3(v)}^1\int_{l_4(v)}^1 wdcdv - C_c y\\&=Nw(\frac{c_0^2-c_0}{\alpha h(y)}+\frac{(\alpha h(y)-1)(\alpha^2h(y)^2-c_0^2)}{2\alpha^2 y})\\&-C_c y.\end{aligned}\tag{17}$$

Hence, the optimal CP decision is to find $y^* \in [0, y_{\max}]$ to maximize his payoff:

$$y^* = arg \max_{y\in[0,y_{\max}]} U_{\text{ECS-CP}}.\tag{18}$$

We notice that $U_{\text{ECS-CP}}(y)$ is a high order polynomial, and may have multiple extreme points, making it hard to derive the closed form of y^*. Hence, we can employ numerical methods to get the approximation of y^*.

With the assumption that $f(c) = 1$ and $g(v) = 1$, U_{ECS-CP} can be computed as:

$$U_{ECS-CP} = N\cdot w\frac{(\beta(y)+1)(\beta(y)-c_0)^2}{2\beta(y)^2} - C_c y,\tag{19}$$

and we can utilize numerical methods to compute the optimal decision y^*.

Once we derive the CP's optimal decision y^*, the total user payoff can be derived. The total user payoff includes the payoffs of initiated requests without sponsoring and with ECS. Thus, we can compute the total user payoff U_n as following:

$$\begin{aligned}U_n &= N\cdot[\int_{l_3(v)}^1\int_{l_4(v)}^1(\alpha h(y^*)v-c_0)dcdv\\&+\int_0^1\int_0^{\min(l_0(v),l_4(v))}(v-c)dcdv]\\&=N\{\frac{(\alpha h(y)-1)\alpha h(y)}{3}[1-(\frac{c_0}{\alpha h(y)})^3]\\&+\frac{c_0-2\alpha h(y)c_0+\alpha h(y)}{2}[1-(\frac{c_0}{\alpha h(y)})^2]\\&+(c_0^2-c_0)(1-\frac{c_0}{\alpha h(y)})+\frac{1}{6}(\frac{c_0}{\alpha h(y)})^3\\&+\frac{1}{3}(1-\alpha h(y))(1-\frac{1-\alpha h(y)}{2})(1-(\frac{c_0}{\alpha h(y)})^3)\\&+\frac{c_0-1+\alpha h(y)}{2}(1-\frac{c_0}{\alpha h(y)})^2)-\frac{c_0^2}{2}(1-\frac{c_0}{\alpha h(y)})\}.\end{aligned}\tag{20}$$

VI. COOPERATIVE AND COMPETITIVE MODELS UNDER COEXISTENCE

In this section, we analyze the model in which CDS and ECS coexist and formulate it in a two-stage decision problem. In the first stage, the CPs decide their sponsor efforts by setting (x, y), respectively. In the second stage, MUs determine their activities according to the CPs' decisions in the first stage. Here, we study the problem in the following two typical scenarios:

- The CPs reach an agreement to cooperate with each other or one CP use both sponsor schemes to attract users. In this scenario, the CPs aim to find the optimal sponsor decision to maximize the sum of their payoffs.
- 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 their own maximal payoff.

Next, we will analyze the problem by backward induction.

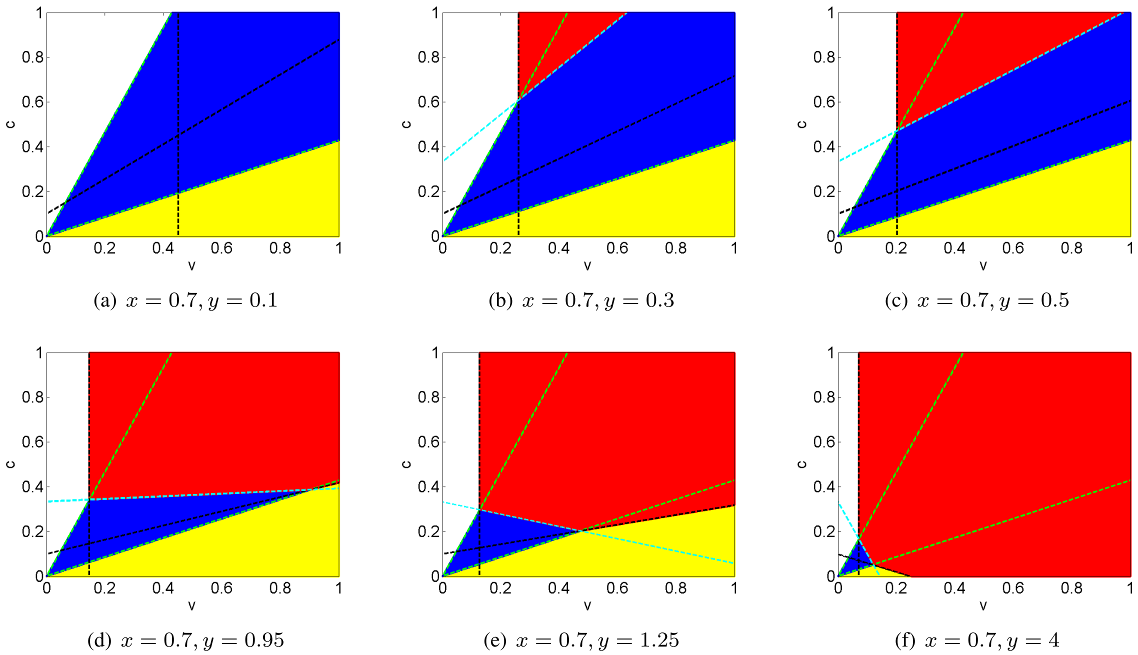


FIGURE 7. Illustration of user decision distribution. (White: not initiated, Yellow: no sponsoring, Blue: CDS, Red: ECS.)

TABLE 1. Notations of important variables.

Notation	Meaning
N	The number of mobile users
L	The number of locations
T	The time set
x	The percentage of sponsored content in CDS
y	The caching effort in ECS
w	The revenue of a sponsoring
C_c	The baseline caching cost
v	The normalized user utility
c	The normalized data cost
$g(v)$	The user distribution of utility
$f(c)$	The user distribution of data cost
$s \in \{N, I, C, E\}$	The user choice
$u_{(v,c)}(s)$	The user payoff under selection s
α	advertisement length fraction
$h(y)$	video quality function
$U_{\text{CDS-CP}}$	the payoff of the CDS-CP
$U_{\text{ECS-CP}}$	the payoff of the ECS-CP
U_{CP}	the payoff of both the CPs
U_n	the payoff of the users

A. 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. Hence, the user decision is $s \in \{N, I, C, E\}$. We can derive the payoff of a type-(v, c) user request as:

$$u_{(v,c)}(s) = \begin{cases} 0, & s = N \\ v - c, & s = I \\ \alpha v - (1-x)c, & s = C \\ \alpha h(y) \cdot v - c_0, & s = E \end{cases} \tag{21}$$

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

$$u_{(v,c)}(I) \geq \max\{u_{(v,c)}(C), u_{(v,c)}(E), 0\}, \tag{22}$$

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

$$u_{(v,c)}(C) \geq \max\{u_{(v,c)}(I), u_{(v,c)}(E), 0\}, \tag{23}$$

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

$$u_{(v,c)}(E) \geq \max\{u_{(v,c)}(I), u_{(v,c)}(C), 0\}, \tag{24}$$

We plot the user distribution under different sponsor decisions in Fig. 7. Let $\eta = \frac{v}{c}$ denotes the *utility-to-cost* ratio. We observe that a user request with very large η tends to refuse the data sponsoring, which is defined as *utility sensitive* request. A user request with a very small η tends to accept the data sponsoring, which is defined as *cost sensitive* request. Moreover, *cost sensitive* requests with large c tend to accept ECS, and requests with small c tend to accept CDS. Intuitively, *utility sensitive* requests care much about utilities even incurring a high cost, and *cost sensitive* requests mean 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:

$$l_5(v) = \frac{1 - h(y)}{1 - x}\alpha v + \frac{c_0}{1 - x}. \tag{25}$$

Together with the former introduced $l_0(v)$, $l_1(v)$, $l_2(v)$, $l_3(v)$, $l_4(v)$, we can derive the user decision distribution. Specifically, we have the following lemma illustrating the user decision distribution:

Lemma 5: 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. 7(a) ∼ Fig. 7(f). We set $x = 0.7$ and multiple values of y in a increasing sequence. When $y = 0.1$, we find in Fig. 7(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 2: 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:

$$U_n = N \cdot [\int_0^{l_3(v)} \int_{[\max(l_0(v), l_2(v)]_0^1}^{1} (v - c)f(c)dcg(v)dv + \int_0^1 \int_{[\min(l_2(v), l_5(v))]_0^1}^{[\min(l_1(v), l_5(v))]_0^1} (\alpha v - c(1 - x))f(c)dcg(v)dv + \int_{l_3(v)}^1 \int_{[\max(l_4(v), l_5(v))]_0^1}^{1} (\alpha h(y)v - c_0)f(c)dcg(v)dv] \tag{26}$$

B. CP'S UTILITY

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:

$$U_{\text{CDS-CP}} = N \cdot \int_0^1 \int_{[\min(l_2(v), l_5(v))]_0^1}^{[\min(l_1(v), l_5(v))]_0^1} (w - c \cdot x)g(v)dvf(c)dc \tag{27}$$

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:

$$U_{\text{ECS-CP}} = N \cdot \int_{l_3(v)}^1 \int_{[\max(l_4(v), l_5(v))]_0^1}^{1} wg(v)dvf(c)dc - C_c y \tag{28}$$

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 two scenarios of cooperative and competitive CPs.

C. COOPERATIVE CPS' BEST DECISION IN STAGE I

We investigate the scenario that the two CPs cooperate with each other to jointly optimize the sum payoff. This corresponds to the practical scenarios: two CPs establish agreement to maximize the total payoff or one CP employs both sponsor schemes to maximize his own payoff. We define $U_{\text{CP}} = U_{\text{CDS-CP}} + U_{\text{ECS-CP}}$ as the sum payoff. In the cooperative scenario, the objective is to maximize U_{CP} by determining sponsor efforts x and y. Therefore, the CP payoff optimization problem can be formulated as

$$\max_{\{x,y\}} U_{\text{CDS-CP}}(x, y) + U_{\text{ECS-CP}}(x, y) \tag{29}$$

We can check that problem (29) is non-convex. Hence it is difficult to obtain the closed form solution of the optimal CPs' decisions (x^*, y^*). As the problem (29) is a two-variable optimization problem with box constraints (i.e., $x \in [0, x_{\max}]$ and $y \in [0, y_{\max}]$), we can solve it using certain numerical methods such as the branch-and-bound method. We define the optimal $y^*(x)$ under any x as:

$$y^*(x) = arg \max_{y \in [0, y_{\max}]} U_{CP}(x, y), \quad \forall x \in [0, x_{\max}]. \tag{30}$$

Similarly, we can derive the optimal $x^*(y)$ under any y as:

$$x^*(y) = arg \max_{x \in [0, x_{\max}]} U_{CP}(x, y), \quad \forall y \in [0, y_{\max}]. \tag{31}$$

Next we provide a numerical method to solve the problem (29) in the sequential manner. First, we find the optimal $y^*(x)$ under any x through one dimensional search. Second, we find the optimal $x^*(y)$ under any y through one dimensional search. Then, we employ the following proposition to prove that the above method can reach the CPs' best strategy.

Proposition 1: The CPs' best strategy (x^*, y^*) must occur at an intersection point of $y^*(x)$ and $x^*(y)$.

With Proposition 1, we design an iterative method, searching x^* and y^*. In the 0-th iteration, x^* is initiated with $x^*(0)$. In the t-th iteration, the algorithm updates $x^*(t)$ by

$$x^*(t + 1) = x^*(y^*(x^*(t))), \tag{32}$$

and the iteration terminates when $|x^*(t + 1) - x^*(t)| < \delta$, where δ is a threshold. Then, y^* can be computed as $y^*(x^*(t))$.

D. COMPETITIVE CPS' BEST DECISION IN STAGE I

In the competitive scenario, the CPs are the players, and they simultaneously 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.*, $\mathcal{C}(y)$. We have

$$\mathcal{C}(y) \in arg \max_{x \in [0, x_{\max}]} U_{\text{CDS-CP}}(x, y). \tag{33}$$

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

$$\mathcal{E}(x) \in arg \max_{y\in[0,y_{\max}]} U_{\text{ECS-CP}}(x, y). \tag{34}$$

Theorem 3: When the CPs' decisions are mutual best responses, we achieve the Nash Equilibrium of the game, denoted by (x^*, y^*), which satisfies

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

Next Theorem characterizes the condition for the existence and uniqueness of the CP best decision equilibrium [29].

Theorem 4: There exists a unique pure CP decision equilibrium (x^*, y^*) if we can find a region $[x_{\min}, x_{\min}+a]$, $a > 0$ with $0 \leq x_{\min} < x_{\min} + a \leq x_{\max}$, and another region $[y_{\min}, y_{\min} + a]$ with $0 \leq y_{\min} < y_{\min} + a \leq y_{\max}$, where $x^* \in [x_{\min}, x_{\min}+a]$ and $y^* \in [y_{\min}, y_{\min}+a]$, if the following conditions are satisfied:

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

In our simulations, we observe that the regions satisfying condition 1), 2) and 3), are not always satisfied. However, we also find that conditions 1) − 3) are sufficient but not necessary conditions, and a CP decision equilibrium may exist even if these conditions are not satisfied. For the simplicity of analysis, we will assume that all three conditions in Theorem 4 are satisfied.

VII. NUMERICAL RESULTS

To evaluate the proposed scenarios, we conduct a Matlab-based numerical study and assume a MBS with a transmission range of 500 m, and a CSBS with a transmission range of 50 m. The range of the CSBS is totally covered by the MBS, hence CDS and ECS coexist within the CSBS 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 stackelberg game jointly, and derive the optimal decision of CPs under cooperative and competitive scenarios.

A. COOPERATIVE AND COMPETITIVE BEST DECISIONS

We first investigate the CPs' optimal decision under cooperative scenario. In this scenario, the objective is to maximize the sum of two CPs' payoff, i.e., to achieve the "Optimal Social Welfare". In Fig. 8, we present the sum of CPs' payoffs, and

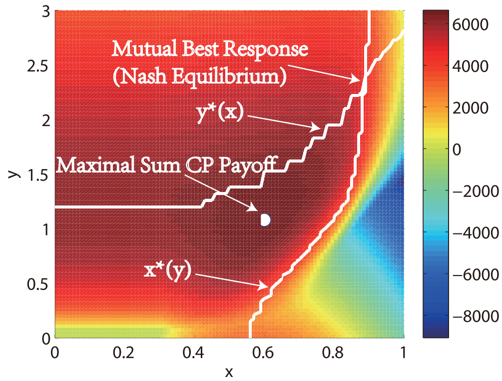


FIGURE 8. Illustration of sum CP payoff and best CP decision under cooperative and competitive scenarios.

the maximum payoff (denoted as "Optimal Social Welfare") is achieved at $(x = 0.61, y = 1.11)$. Fig. 8 shows that social welfare increases with x or y when the sponsoring efforts are small, because the two sponsor schemes attract different types of requests and meet little competition. When the sponsor efforts x and y are large enough, the sum payoff begins to decrease with x and y. The possible reasons are listed as follows:

- In pure CDS or ECS, the CP's has an optimal sponsor effort decision. Once the sponsor effort is larger than the optimal effort, the CP's payoff decreases. Due to the coexistence of the two sponsor schemes, the threshold causing the CP's payoff to decrease should be smaller than in the pure sponsor scenario. Thus, once both the CPs' payoffs decrease with the sponsor effort, the sum payoff decreases.
- We notice the analysis in Fig. 7 that when the sponsor effort is large, the competition between CDS and ECS is more fierce. In this case, the added sponsor effort will cause users choosing the other sponsor scheme fewer. This induces much cost for the CP but creates little revenue, hence cause the sum payoff decrease.

Next, we compare the optimal decision under cooperative and competitive scenarios in Fig. 8. We plot the optimal CDS-CP's decision $x^*(y)$, and the optimal ECS-CP's decision $y^*(x)$ in this figure. By calculate the interaction of the two curves, we get a point $(x^* = 0.88, y^* = 2.45)$ which is the CP's optimal decision under the competitive scneario. We observe that the optimal CP decision under competitive scenario is larger that the decision under cooperative decision. This implies that when the two CPs cooperate, they will spend less sponsor effort to reduce cost as they need not to compete for additional users any more.

Next, we investigate the MUs' payoff under different scenarios. As analyzed above, we know that CPs under cooperative scenario will pay less sponsor effort than under competitive scenario. This will cause the MUs' payoff under cooperative scenario less than under competitive scenario, as fewer MUs will be sponsored with a lower sponsor effort. Fig. 9 shows the MUs' payoff under best competitive and

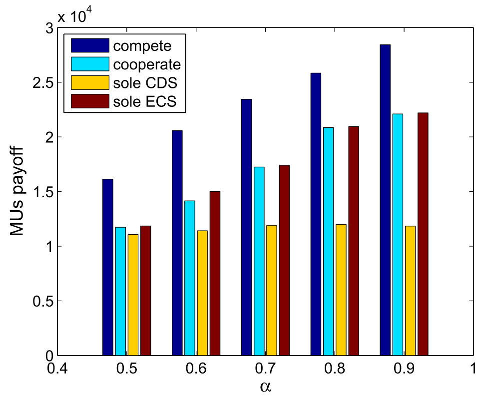
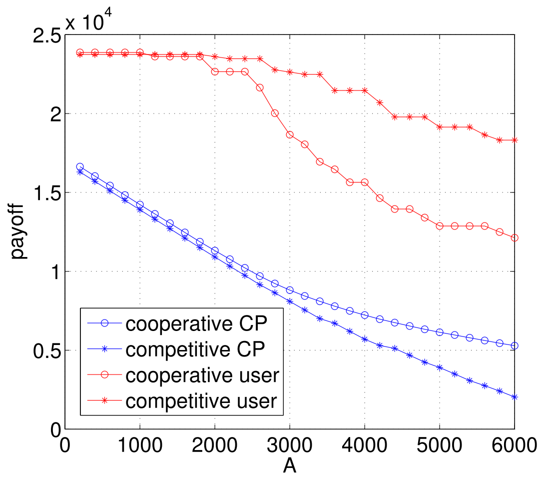
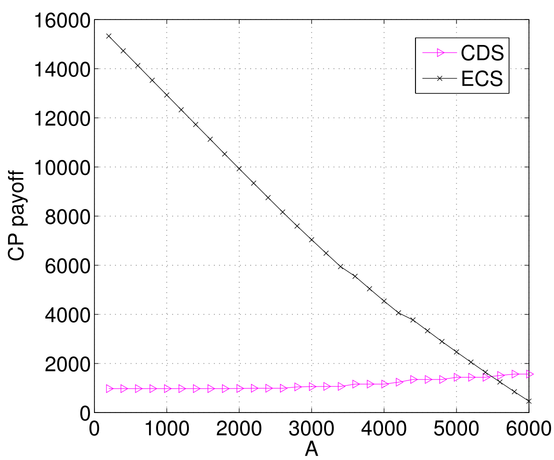


FIGURE 9. **MUs' payoff versus α.**



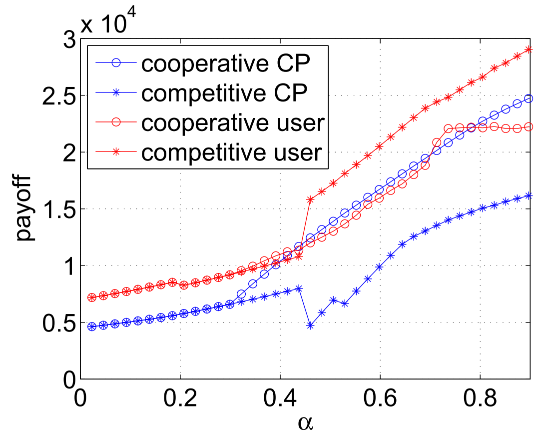
(a)



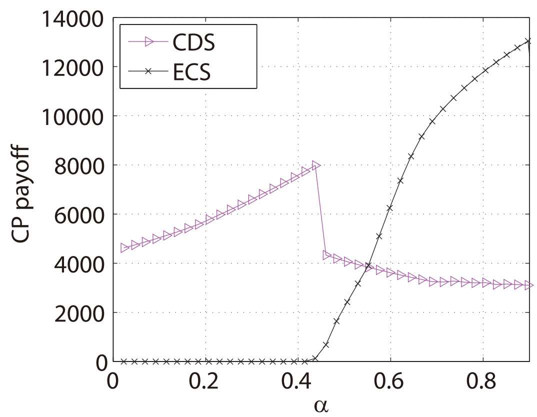
(b)

FIGURE 10. **(a) sum CP payoff and user payoff versus caching cost *A*, (b) CDS-CP and ECS-CP payoffs versus caching cost *A*.**

cooperative scenarios, with sole CDS and ECS as baseline. We observe that MUs' payoff under competitive scenario is always larger than other scenarios. 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.



(a)



(b)

FIGURE 11. **(a) sum CP payoff and user payoff versus sponsor discount α, (b) CDS-CP and ECS-CP payoffs versus sponsor discount α.**

We further find that when $\alpha = 0.6$, the payoff under sole ECS is higher than under cooperative scenario. This indicates that the cooperation of CPs may harm the user benefit.

B. IMPACTS OF IMPORTANT PARAMETERS

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

1) IMPACT OF CACHING COST *A*

We plot the user payoff and the sum CP payoff in Fig. 10(a) versus caching cost in edge network A. Fig. 10(a) reveals that sum CP payoff decreases in both competitive and cooperative scenarios, as the large caching cost harms ECS-CP's payoff directly, and further reduce the sum CP payoff. We also notice that CP payoff is larger under cooperative scenario than under competitive scenario. Moreover, user payoff monotonically decreases with caching cost, because a high caching cost will cause the ECS-CP pay less sponsor effort. The user payoff is higher when CPs compete with each other.

In Fig. 10(b), we plot the single CP payoff versus caching cost. The x-axis is the caching cost, and the y-axis represents the payoffs of both ECS-CP and CDS-CP. We can observe that ECS-CP's payoff decreases with caching cost A.

Consequentially, CDS-CP's payoff increases slightly due to less competition.

2) IMPACT OF SPONSOR DISCOUNT α

Recall that the sponsor discount α is induced by the extra attached advertisement. Fig. 11(a) presents that when $\alpha < 0.3$, the CP payoff under the two scenarios are equal, because the two CPs barely compete for user request when α is small. We also observe that when $\alpha \geq 0.74$, the user payoff reaches the upper-bound in the cooperative scenario, which is due to the avoidance of the CPs competition. We can observe from Fig. 11(b) that when $\alpha \leq 0.44$, the best decision for ECS-CP is paying no effort. When $\alpha > 0.44$, ECS-CP's payoff increases with α. We conclude that ECS-CP is α- *sensitive*, as the payoff of CDS-CP increases with w.

VIII. CONCLUSION

In this paper, we first showed the challenges and opportunities using different sponsoring schemes, i.e., CDS and ECS. We investigated cooperative and competitive scenario and formulated the problem using a two-stage Stackelberg game. In the first scenario, we focus on achieving the maximal total benefit of content providers by optimizing CDS and ECS schemes together. In the second scenario, we separately optimize ECS and CDS schemes and maximize the benefits of corresponding content providers. Our trace-driven evaluation showed that the CPs under cooperative scenario will pay less than the CPs under competitive scenario and the CPs' competition can be increased 36%-140% from MUs' payoff.

APPENDIX
IMPORTANT PROOFS
A. PROOF OF LEMMA 3

$$\begin{aligned}
U_{\text{CDS-CP}} &= \int_0^1 \int_{\frac{1-x}{\alpha}c}^{\lceil \frac{x}{1-\alpha}c \rceil^1} g(v)dv \cdot (w - c \cdot x) f(c) dc \\
&= \int_0^{\frac{1-\alpha}{x}} \int_{\frac{1-x}{\alpha}\cdot c}^{\frac{x}{1-\alpha}\cdot c} dv \cdot (w - c \cdot x) dc \\
&\quad + \int_{\frac{1-\alpha}{x}}^1 \int_{\frac{1-x}{\alpha}\cdot c}^{1} dv \cdot (w - c \cdot x) dc \\
&= \int_0^{\frac{1-\alpha}{x}} \left(\frac{x}{1-\alpha} - \frac{1-x}{\alpha}\right) \cdot (w - c \cdot x) dc \\
&\quad + \int_{\frac{1-\alpha}{x}}^1 \left(1 - \frac{1-x}{\alpha} \cdot c\right) \cdot (w - c \cdot x) dc \\
&= \frac{(1-\alpha)^2}{6 \cdot x} - \frac{w \cdot (1-\alpha)}{2 \cdot x} - \frac{w \cdot (1-x)}{2 \cdot \alpha} \\
&\quad + \frac{x \cdot (1-x)}{3 \cdot \alpha} + w - \frac{x}{2}.
\end{aligned}$$

We can derive that:

$$\begin{aligned}
U'_{\text{CDS-CP}} = -\frac{1}{6 \cdot \alpha \cdot x^2} &\cdot (4 \cdot x^3 + (3 \cdot \alpha - 3 \cdot w - 2) \cdot x \\
&+ 3\alpha \cdot (1-\alpha) \cdot w + \alpha(1-\alpha)^2).
\end{aligned}$$

We can further derive that:

$$U''_{\text{CDS-CP}} = \frac{(1-\alpha-3w)(1-\alpha)}{3x^3} - \frac{2}{3\alpha}.$$

When $1 - \alpha - 3w \leq 0$, hence $3w + \alpha \geq 1$, $U''_{\text{CDS-CP}} < 0$, $\forall x > 0$.

B. PROOF OF THEOREM 1

When $3w + \alpha \geq 1$, $U''_{\text{CDS-CP}} < 0, \forall x > 0$. Then we can derive that $U'_{\text{CDS-CP}}$ is monotone decreasing. We also know from Lemma 2 that $x \in [1-\alpha, 1]$. If $U'_{\text{CDS-CP}}(1) \geq 0$, then $U'_{\text{CDS-CP}}(x) \geq 0, \forall x \in [1-\alpha, 1]$, and $U_{\text{CDS-CP}}$ is monotone increasing. So the best decision is $x^* = 1$.

We can prove the best decision is $x^* = 1 - \alpha$ when $U'_{\text{CDS-CP}}(1-\alpha) \leq 0$ in the similar way.

If neither conditions above exist, the maximal value is within $[1-\alpha, 1]$.

C. PROOF OF THEOREM 3

As user decisions are not coupled with each other, when the CPs decide the sponsoring efforts x and y, we can compute each user request's identical payoff of different selections $u_{(v,c)}(s), \forall s = \{N, I, C, E\}$. By selecting the maximal user payoff, we can derive the unique user choice. As each user decision is fixed, the NE in Stage II is achieved.

D. PROOF OF THEOREM 4

We can find another variable $x_u = x - x_{\min}$, satisfying $\mathcal{E}(x) = \mathcal{E}'(x_u), \forall x_u \in [0, a]$. Similarly, we can find $y_u = y - y_{\min}$ and $\mathcal{C}'(y_u), \forall y_u \in [0, a]$.

Consider two sponsoring efforts x_u^1 and x_u^2 ($x_u^1 < x_u^2$). Since $\mathcal{E}'(x_u)$ and $\mathcal{C}'(y_u)$ are increasing, we have $\mathcal{E}'(x_u^1) < \mathcal{E}'(x_u^2)$ and $\mathcal{C}'(\mathcal{E}'(x_u^1)) < \mathcal{C}'\mathcal{E}'(x_u^2))$. For convenience, we use $\mathcal{F}(\cdot)$ to refer $\mathcal{C}'(\mathcal{E}'(\cdot))$. $\mathcal{F}(\cdot)$ is non-decreasing. Due to $\mathcal{F}(0) \geq 0$ and $\mathcal{F}(a) \leq a$, we know that $0 \leq \mathcal{F}(x) \leq a$ if $0 < x < a$. According to Theorem 12.5 of [40], there exists one fixed point satisfying $\mathcal{F}(x) = x$, which indicates the existence of NE.

Now we prove the uniqueness of NE by contradiction. Assume that there exist two NEs, *i.e.*, $(x_u^a, \mathcal{E}(x_u^a))$ and $(x_u^b, \mathcal{E}(x_u^b))$. Without loss of generality, we suppose $x_u^a > x_u^b$. According to condition 3), we have $\mathcal{E}(x_u^a) - x_u^a < \mathcal{E}(x_u^b) - x_u^b$. We also know $\mathcal{E}(x_u^a) \geq \mathcal{E}(x_u^b)$. Therefore, we have $\mathcal{F}(x_u^a) - \mathcal{E}(x_u^a) \leq \mathcal{F}(x_u^b) - \mathcal{E}(x_u^b)$. We have $\mathcal{F}(x_u^a) - x_u^a = 0$ holds. Then we have

$$\begin{aligned}
\mathcal{F}(x_u^b) - x_u^b &= \mathcal{F}(x_u^b) - \mathcal{E}(x_u^b) + \mathcal{E}(x_u^b) - x_u^b \\
&> \mathcal{F}(x_u^a) - \mathcal{E}(x_u^a) + \mathcal{E}(x_u^a) - x_u^a = 0, \quad (35)
\end{aligned}$$

which contradicts the assumption that $(x_u^b, \mathcal{E}(x_u^b))$ is an NE.

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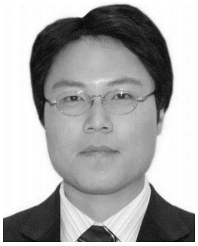

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