On the Economic Impact of Telco CDNs and their Alliance on the CDN Market

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***Abstract*—The CDN (Content Delivery Network) market consists of content providers (CPs), Internet service providers (ISPs), and CDN providers and evolves based on their complex cooperation and competition. Recently, the rapid growth of content-oriented traffic has brought forth a new entity called *Telco CDNs* in the content delivery supply chain, where Telco CDNs are the ISP-operated CDN providers, vertically integrating content delivery service with traffic engineering, so as to provide better reliability and QoS to users and reduce infrastructure investments. Telco CDNs and traditional CDNs would compete for their market shares with their unique advantages: Telco CDNs are capable of jointly optimizing network costs and user-perceived QoS, but possibly with their geographical limitation in service areas, whereas traditional CDNs operate a network of servers worldwide, with the advantages of performing global, sophisticated analytics or providing better security solutions. Telco CDNs may form an alliance (e.g., cache server sharing) to compete with traditional CDNs, but with some alliance cost. With this CDN market evolution, this paper conducts a game-theoretic study of when and how traditional CDNs survive in the competition with Telco CDNs. In particular, our study answers the questions about the impact of Telco CDNs' unique characteristics on the long-term competition against traditional CDNs, and the impact of Telco CDNs' alliance. Our analysis provides useful implications on the economics of the future CDN market, e.g., what factors can be Achilles' heel and thus what features should be more focused for Telco and traditional CDNs.**

I. Introduction

A content delivery network (CDN) is a large-scale distributed system consisting of many servers deployed in multiple data centers in the Internet, with the goal of serving contents to end users with high availability and good QoS [1]. Existing CDN vendors with large market shares include Akamai, Limelight, and CD Networks [2]. The role of a CDN is to help content providers (CPs), the CDNs' customers by replicating popular contents in their servers typically in the vicinity of the Internet service providers (ISPs) with which the CDN has contracts. There are several advantages of CDNs. First, server load is reduced since content requests are distributed to multiple servers. Second, since users will be served from nearby servers, delay would be reduced. Third, CDNs provide CPs a degree of content/system protection from outside attacks (e.g., DDoS) by using their large-scale server infrastructure to absorb attack traffic. Clearly, CDNs play a crucial part of the digital supply chain for the delivery of information goods [3]. The supply chain consists of (i) CPs that are responsible for the creation of contents, (ii) backbone and access network service providers (e.g., telcos or ISPs such as AT&T) that own the underlying network and transport contents, and finally (iii) CDNs that optimize content delivery to end users.

Such a tripartite structure of the content delivery market has recently witnessed a big change that a new type of player called *Telco CDNs* have emerged. The rapid growth of Internet traffic, especially video traffic [4] incurs large capital expenditures to broadband ISPs in order to meet the demand and to retain subscribers [5], but Telcos make a marginal diminishing revenue since the traffic value in terms of its volume is best thought of on a logarithmic scale [6]. To address this, telcos or ISPs have increasingly launched their own CDNs as a way of lessening backbone traffic volume and reducing infrastructure investments. AT&T announced a new CDN service in the year of 2011 which enables contents to be directly served by its 38 data centers [7]. In the same year, British Telecom unveiled a new service "Content Connect" [8] to offer consumers a better quality video and TV content, see [9] for more Telco CDNs worldwide as of 2011.

Telco CDNs and traditional CDNs have their own separate *vertical* and *horizontal* merits, respectively. Telco CDNs are operated by ISPs and thus they can vertically control both content distribution and traffic engineering and jointly optimize network cost and user-perceived QoS, as studied in [10]–[14]. However, Telco CDNs also have horizontal demerits in the sense that telcos have their exclusive service areas (e.g., AT&T in US, BT in UK, etc.), hindering them from doing a large-scale content delivery business. On the contrary, traditional CDNs have "global" business, i.e., operate a network of servers around the world, resulting in large horizontal merits. The network of massive servers worldwide generates a large volume of traffic and this enables them to perform sophisticated analytics of their content service, which can be used to provide better security and reliability [15]. Telco CDNs are also making extensive efforts to overcome their geographical limitation in service areas by forming alliances and running virtually global CDNs, as discussed in IETF with the name *CDNi (CDN Interconnection)* [16].[1] These merits and demerits of Telco CDNs and traditional CDNs would incur interesting, non-trivial tensions when they compete in the CDN market.

In this paper, we aim at understanding how economically the CDN market will evolve with the advent of Telco CDNs by understanding the strategic interactions under various scenar-

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[1] This is also referred to as 'CDN federation' in other materials, e.g., [17]

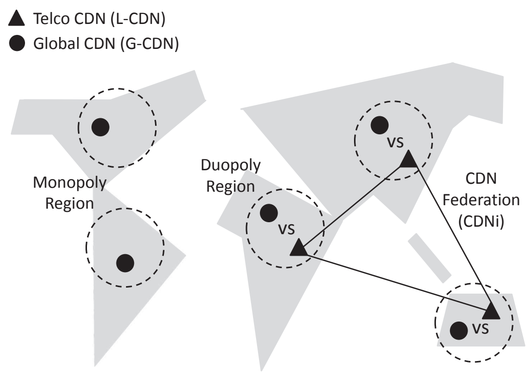


Fig. 1. Monopoly and duopoly regions. The triangle represents the CDN federation (CDNi) among three Telco CDNs in each regions.

ios. We are generally interested in when and how traditional (or Telco) CDNs survive in this market evolution. In particular, we study how the unique merits and demerits of each of the two types of CDNs have impacts on their market shares and revenues, and how economically viable Telco CDNs' cooperation is in competing with traditional CDNs. To that end, we take a game-theoretic approach that models the strategic interactions between two CDNs. We divide the entire region into *duopoly* and *monopoly*. In duopoly regions, both Telco CDNs and traditional CDNs exists and compete, whereas in monopoly regions, only traditional CDNs exist for content delivery service, as seen in Fig. 1. The key features of our model lies in (i) for Telco CDNs, efficiency of joint operation of traffic engineering and content distribution and the size of Telco CDNs' alliance, and (ii) for traditional CDNs, efficiency of global business.[2] We now summarize the main messages of this paper in what follows:

(a) When L-CDNs launch their CDN service without significant operational efficiency (e.g., joint traffic engineering and content distribution), a cutthroat price competition occurs between L- and G-CDNs, resulting in high revenue reduction of both CDNs.
(b) However, if L-CDNs provide sufficient vertical merits and local expertise (thus better QoS than G-CDNs) to users, the L-CDNs obtain a larger market share even with appropriately higher price, leading to reduction of market competition. This in turn results in the growth of the total CDN market revenue.
(c) Generally, forming alliance of L-CDNs helps in the competition with G-CDNs, i.e., L-CDNs revenue increases with the growing size of alliance. The increasing rate depends on the degree of horizontal efficiency of G-CDNs. However, lack of "global know-how" (e.g., maturity in terms of security and big-data analytic) of L-CDNs also increases with growing alliance sizes, which causes the L-CDNs' revenue to decrease when the alliance size exceeds some threshold value.

[2]Throughput this paper, we henceforth refer to traditional CDNs that operate a global network of CDN servers as *G-CDN (Global CDN),* and similarly, we use the terminology *L-CDN (Local CDN)* to mean a Telco CDN that serve only a specific region.

II. Model

A. System Model

Global and Local CDNs. The total CDN market consists of N disjointed regions $\mathcal{R} = \{1, 2, \ldots, N\}$, and we assume that the CDN market size (i.e., the total revenue and the number of CPs) of each region is homogeneous. We refer to traditional CDNs that operate a global network of CDN servers, such as Akamai and Limelight, as *G-CDN (Global CDN).* Similarly, we use the terminology *L-CDN (Local CDN)* to mean a Telco CDN that serve only a specific region, operated by a telco (see Fig. 1). We assume that there exists only a single G-CDN in the market, where all regions can be covered by the G-CDN. One L-CDN can serve only a single region in case of no "federation" with other L-CDNs (we will explain the notion of federation shortly), and each region can be served by at most one L-CDN. Note that there may exist a region served only by G-CDN. Then, we can classify all regions into either *duopoly* or *monopoly* regions. As the name implies, in a duopoly region, both the G-CDN and an L-CDN serves, but only G-CDN exists in a monopoly region (Fig. 1). Let $N_d < N$ be the number of L-CDNs, which implies that there exists N_d duopoly regions. We assume that L-CDNs are homogeneous in the sense that all N_d L-CDNs have the same service quality. Let $N_m = N - N_d$ be the number of monopoly regions, and $\mathcal{N}_d$ be the set of all duopoly regions.

Content providers (CPs). We assume that there are N CPs ($\text{CP}_i : i \in \mathcal{R}$), where CP_i is located in the region i of N regions (i.e., CP_i is provided the Internet connectivity by the region i telco). CP_i requires its own content service coverage $\text{CP}_i^{\text{serv}}$ (e.g., a web portal in Korea wants to launch a content service in Korea, Japan, and Africa). Thus, $\text{CP}_i^{\text{serv}} \subset \mathcal{R}$, and we assume that i is always in $\text{CP}_i^{\text{serv}}$. We assume that the *number* of required service coverage of a CP, which is denoted by $|\text{CP}_i^{\text{serv}}|$, is uniformly random and also homogeneous for all regions. Under this assumption, we will perform an average analysis of CPs and CDNs.

Federation of L-CDNs. We now introduce the notion of *federation* of L-CDNs (or L-CDNs' interconnection, *CDNi* in short) that enables an L-CDN i to provide the content service from CP_i to the users in other regions. This is technically possible by content caching and content request forwarding between federated (or interconnected) L-CDNs [16]. For example, when a user in the region j wants to retrieve a content from CP_i, the user first sends the content request to CP_j, which is forwarded to L-CDN i by the L-CDN j to retrieve the content and deliver (or directly delivers the content from L-CDN j's cache) to the user.

For simplicity, we consider only two cases: (i) all N_d L-CDNs are federated, or (ii) no federation occurs. Each case generates a different type of markets for CPs as follows:

(i) *No federation.* When a CP_i requires more than one region for its service coverage, i.e., $|\text{CP}_i^{\text{serv}}| > 1$, a monopoly market for CP_i is formed. Otherwise, we have a duopoly market for CP_i.

(ii) *Federation.* In case when there exists an L-CDN in region i, whose federated N_d regions contain (resp. does not contain) the service coverage requested by CP_i, a duopoly (resp. monopoly) market is formed for CP_i. Obviously, if no L-CDN exists in region i, only a monopoly market is formed for CP_i.

We comment that duopoly/monopoly *regions* differ from duopoly/monopoly *markets,* where the former and the latter are defined with respect to regions and the CP, respectively. We henceforth use the subscripts g, l to indicate G-CDN and L-CDN, and the superscripts m, d to indicate the type of CDN *markets*, monopoly or duopoly.

III. Game Formulation

We formulate a non-cooperative game among CDN providers and CPs. To that end, we start by presenting the utility of CPs and the revenues of L- and G-CDNs.

A. Utility and Revenue

Utility of CP. We model CPs' heterogeneity by introducing a type parameter θ, which represents the willingness to pay or the preference for the quality of CDN service, assumed to be uniformly distributed in the interval $[0,1]$. The following two key factors change the utility function form of a CP: the types of a market (duopoly/monopoly) and the serving CDN (L-CDN/G-CDN). Different utilities come from different service qualities of serving CDNs, and the existence of competition. We denote $U_i^j(\theta)$ as the utility of type-θ CP for adopting CDN i in market type j. In this context, we have the following three utility function forms (note that L-CDN can serve the CP only in a duopoly market, thus U_l^m is not considered here):

$$\begin{aligned} U_g^m(\theta) &= \theta\kappa_g - p_g^m, \\ U_g^d(\theta) &= \theta\kappa_g - p_g^d, \\ U_l^d(\theta) &= \theta\kappa_l - p_l^d - m\mu, \end{aligned} \tag{1}$$

where m is the size of an L-CDN's service coverage (i.e., $m = N_d$ for federation, and $m = 1$, otherwise), κ_g and κ_l are the *content delivery quality* (e.g., delay) of G-CDN and L-CDN, p_g^m, p_g^d, p_l^d are the CDN prices for all types of market, and μ is the disutility due to a lack of *global know-how* of L-CDNs. The word "global know-how" refers to the expertise of global business, e.g., efficiency of big data treatment and sophisticated analytics worldwide. Clearly, G-CDNs have larger global know-how due to its wider service coverage and longer business history. Note that as more L-CDNs federate, the content service quality of L-CDN deteriorates due to the lack of central authority that can optimize the increasing service coverage, which is reflected in the third term of U_l^d, i.e., $m\mu$.

Revenue of CDNs. Here, our interest is to model the (average) revenue of each type of CDN, which differs for each specific market type. The average revenue is computed by: We first choose a (typical) CP (equivalently choose a typical region, say i, because of the assumption of one CP per one region), and compute the average revenues of L-CDN and G-CDN for the possible market types.

First, the average revenue π_l of an L-CDN is given by[3]:

$$\begin{aligned} \pi_l &= \mathbb{P}[\text{CP}_i \in \mathcal{N}_d] \times \mathbb{P}[\text{duopoly market for CP}_i] \times \pi_l^d \\ &= \frac{N_d}{N} \times \mathbb{P}\Big[|\text{CP}_i^{\text{serv}}| \le m\Big] \times \pi_l^d, \end{aligned} \tag{2}$$

where recall that m is L-CDN's coverage, and π_l^d the average revenue conditioned on duopoly market.

Next, similarly to L-CDN, we can easily express the average revenue of G-CDN by:

$$\begin{aligned} \pi_g = &\frac{N_d}{N} \times \mathbb{P}\Big[|\text{CP}_i^{\text{serv}}| \le m\Big] \times \pi_g^d \\ &+ \frac{N_d}{N} \times \mathbb{P}\Big[|\text{CP}_i^{\text{serv}}| > m\Big] \times \pi_g^m + \big(1 - \frac{N_d}{N}\big) \times \pi_g^m, \end{aligned} \tag{3}$$

where π_g^d, π_g^m are defined similarly to π_l^d, e.g., π_g^d is the average revenue of G-CDN in the duopoly market.

Now, the per-market average revenues $\pi_l^d, \pi_g^d, \pi_g^m$ are computed by considering the notion of *market share*, quantified by the length of the subinterval contained in the entire CP-type interval $[0,1]$, in which G-CDN (resp. L-CDN) is selected by a typical CP through the game. Recall that we modeled the type of CP by a uniform random variable θ. Thus, by denoting $\theta_l^d, \theta_g^d, \theta_g^m$ to be the market shares of all possible cases of CDN/market combination, we have: $\pi_l^d = p_l^d\theta_l^d$, $\pi_g^m = p_g^m\theta_g^m$, and $\pi_g^d = p_g^d\theta_g^d$.

B. Profit Maximization of CDNs

A CDN's strategy is the market-dependent *price,* (i.e., p_l^d, p_g^d and p_g^m), and they set a price for maximizing the revenue. Then, a type-θ CP either selects a CDN that maximizes its utility or decides not to use a CDN if it gives negative utility. We denote the strategy of type-θ CP as $s(\theta) \in \{g, l, n\}$, where again g and l stand for G-CDN and L-CDN, respectively, while n designates no selection of any of the CDNs if their revenues become negative. We now describe the game for each of the market types.

Monopoly market. The CP in a monopoly market is only served by the G-CDN. G-CDN decides the optimal price to maximize his revenue π_g^m by solving the following problem:

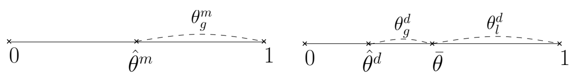
$$\textbf{G-CDN}: \quad \max_{p_g^m \ge 0} \pi_g^m. \tag{4}$$

A type-θ CP selects the service $s^*(\theta) \in \{g, n\}$ that maximizes his utility:

$$\textbf{CP}: \quad s^*(\theta) = \arg\max_{s \in \{g,n\}} U_s(\theta). \tag{5}$$

Let $\hat{\theta}^m = \{\theta \,|\, U_g(\theta) = U_n(\theta)\}$, where $U_n(\theta) = 0$. The value $\hat{\theta}^m$ corresponds to the type threshold of a CP under which the CPs obtain negative utility when they use G-CDN. Then, the market share of G-CDN is given by $\theta_g^m = 1 - \hat{\theta}^m$.

[3] Throughout this paper, for tractable analysis, we assume that a CP has "location-independent" service coverage requests, i.e., the CP is just interested in the number of requested regions actually served by federated L-CDNs. This assumption seems to hold in practice, because L-CDNs are also ISPs that provide network connectivity and are highly likely to be located in the regions where most content requests are generated.



(a) Monopoly Market (b) Duopoly Market

Fig. 2. Market shares: (a) monopoly, and (b) duopoly. (Note that (b) is one example among four possible market shares in a duopoly region as shown in Fig. 3.)

Duopoly Market In a duopoly market, i-CDN, $i \in \{G, L\}$ selects the optimal price that solves the following problem:

$$i\textbf{-CDN :} \quad \max_{p_i^d \geq 0} \pi_i^d. \tag{6}$$

A type-θ CP chooses the service $s^*(\theta)$ among three service types to maximize his utility:

$$\textbf{CP :} \quad s^*(\theta) = \arg \max_{s \in \{g,l,n\}} U_s(\theta). \tag{7}$$

Similar to $\hat{\theta}^m$, we denote $\hat{\theta}^d$ as the type of indifferent CP in using the CDN service in a duopoly market, i.e., $\hat{\theta}^d = \min\big(\{\theta \,|\, U_l(\theta) = 0\}, \{\theta \,|\, U_g(\theta) = 0\}\big)$. We further denote $\bar{\theta}$ as the type of indifferent CP in using either of G-CDN and L-CDN, i.e., $\bar{\theta} = \{\theta \,|\, U_l(\theta) = U_g(\theta)\}$.

IV. Impact of L-CDN's Quality on the CDN Market

The key question we address in this section is how the unique characteristics of Telco CDNs affect the long-term competition against a traditional CDN. The unique characteristic implies the advantages in operating CDN such as the optimization of network cost and user-perceived latency.

A. L-CDN in Duopoly: Non-trivial Scenarios

Prior to the concrete analysis in subsequent sections, we first filter out trivial scenarios for L-CDN. It is intuitive that if a CDN with low content delivery quality sets a high price, its market share will be small. To formally study, consider the (perceived) *price per unit quality* of L-CDN, defined by:

$$\frac{p_l^d + m\mu}{\kappa_l},$$

where note that $p_l^d + m\mu$ corresponds to the cost incurred to CPs for using L-CDN, which is the sum of disutility due to the lack of global know-how and the CDN service fee. Similarly, the price per unit quality of G-CDN is denoted by p_g^d/κ_g. Using the notion of price per unit quality and the content delivery quality parameter, we classify the type of an L-CDN in a duopoly market into one of the following four cases:

LL. $\kappa_l < \kappa_g$ and $\frac{p_l^d + m\mu}{\kappa_l} < \frac{p_g^d}{\kappa_g}$.

LH. $\kappa_l < \kappa_g$ and $\frac{p_l^d + m\mu}{\kappa_l} > \frac{p_g^d}{\kappa_g}$.

HL. $\kappa_l > \kappa_g$ and $\frac{p_l^d + m\mu}{\kappa_l} < \frac{p_g^d}{\kappa_g}$.

HH. $\kappa_l > \kappa_g$ and $\frac{p_l^d + m\mu}{\kappa_l} > \frac{p_g^d}{\kappa_g}$.

LL corresponds to the case when an L-CDN in a duopoly market has a lower content delivery quality and sets a lower perceived price per unit quality than the G-CDN. Similarly, **LH**, **HL**, and **HH** can be interpreted. As formally analyzed in our technical report [18], for all of the four cases, we have the market share divisions, as shown in Fig. 3, from which we see that **LH** and **HL** are not highly interesting in the sense that just either L-CDN or G-CDN dominates the market (i.e., boundary equilibrium). Thus, we henceforth perform the main analysis with only **LL** and **HH** (i.e., interior equilibrium) in the following sections.

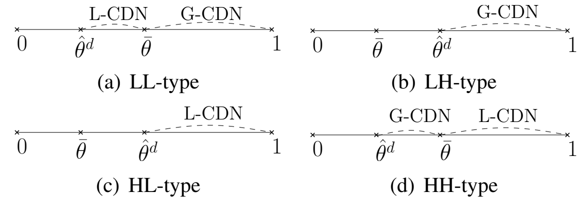


Fig. 3. Market shares in duopoly market depending on the four different types of L-CDN.

B. With Low Quality L-CDN (LL-type)

First, we focus on the case where L-CDNs provide lower quality CDN services than G-CDN, i.e., **LL**. Low quality L-CDNs occur if Telco CDNs have not enough advantages in operating CDN due to the lack of investment or the traditional CDN already has highly well-developed content delivery system, thus Telco CDNs cannot catch up with the quality of service of the traditional CDN. We first show how a low quality L-CDN changes the revenues of the CDN market and the traditional CDN.

Proposition 1 Under the **LL** condition, the aggregate average revenue of G-CDN and L-CDN (i.e., $\pi_g + \pi_l$) always decreases in the number of L-CDNs, N_d.

Implications. Due to space limitation, the detailed proof is presented in [18]. We introduce a sketch of proof and explain implications of above proposition. A CDN market corresponding to a CP$_i$ ($i \in \mathcal{R}$) is changed to duopoly market from monopoly market, if an L-CDN initiates its service in region i and the service coverage of the L-CDN i accommodates the required coverage of the CP$_i$. Note that the total number of markets is same as the number of CPs, which is N. It implies that the number of duopoly market (resp. monopoly market) increases (resp. decreases) with the number of L-CDNs. Thus, the aggregate average revenue of G-CDN and L-CDN decreases if the aggregate revenue of duopoly market (i.e., $\pi_g^d + \pi_l^d$) is less than the revenue of monopoly market (i.e., π_g^m).

In duopoly market, the optimal prices of L-CDN and G-CDN are less than that of G-CDN in monopoly market (i.e., $p_l^d < p_g^m, p_g^d < p_g^m$) because of the price competition of CDN providers. The lower optimal prices induce the enlargement of total market share of CDN market (i.e., $\theta_g^d + \theta_l^d > \theta_g^m$.) since the CPs with low preference (or willingness to pay) on CDN service would come into the market. However, while the market share is increasing, it cannot compensate the drop in prices due to competition. Thus, the revenue of duopoly market is less than that of monopoly market.

C. With High Quality L-CDN (HH-type)

Next we consider the CDN market with L-CDNs having high quality and high price per unit quality. In contrast to a

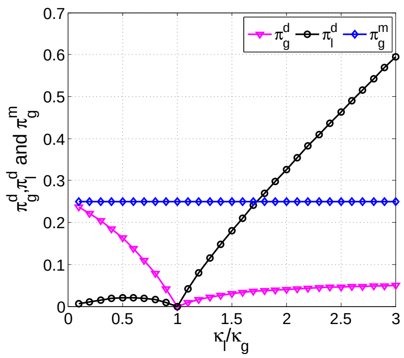


Fig. 4. When $\mu = 0$, revenues of providers in duopoly and monopoly market with respect to the relative quality of CDNs. ($\kappa_g = 1$, $0.1 \leq \kappa_l \leq 3$)

low quality L-CDN, a high quality L-CDN occurs when a telco CDN makes relatively high investments or when the traditional CDN is not well-developed.

Proposition 2 Under the **HH** condition, if $\mu = 0$, the aggregate average revenue of G-CDN and L-CDN (i.e., $\pi_g + \pi_l$) increases in the number of L-CDNs, N_d, if

$$16\left(\frac{\kappa_l}{\kappa_g}\right)^3 - 28\left(\frac{\kappa_l}{\kappa_g}\right)^2 + 4\left(\frac{\kappa_l}{\kappa_g}\right) - 1 > 0. \tag{8}$$

Implications. The proof is presented in [18]. Similar to Proposition 1, the aggregate revenue of G-CDN and L-CDN increases with the number of L-CDNs if the revenue in a duopoly market is larger than that in a monopoly market. Here, we consider the case without global know-how (i.e., $\mu = 0$). When κ_g is fixed, the optimal prices of L-CDN and G-CDN increase with κ_l. For L-CDN, it is obvious that he could set a higher price with a higher quality. Also, since competition weakens as κ_l moves away from κ_g, G-CDN could set a higher price as well. As prices increase, the market shares decrease accordingly. However, the market share has a lower bound from which it no longer decreases. This is because the price is set such that the profit is maximized and thus the rate of price increase due to the increase in quality will be constrained to make the market share at least above some value. Eventually, as prices go up while the market shares are bounded below, the total revenue of CDN market increases with the advent of L-CDN with sufficiently high quality.

D. Asymptotic Behavior of Revenue with respect to Relative Quality

Fig. 4 depicts how the revenues of providers (and total CDN market) vary with the quality of L-CDN. We fix the quality of G-CDN by unity, and change the quality of L-CDN from 0.1 to 3. First, we observe the following result.

$$\lim_{\kappa_l/\kappa_g \to 1} p_l = \lim_{\kappa_l/\kappa_g \to 1} p_g = 0$$

If the CDNs provide with the same quality, they engage in a symmetric Bertrand duopoly with 0 marginal cost. Thus, the price (and hence the revenue) of each CDN decreases to 0 as the quality of both CDNs becomes more similar due to the intensifying competition. Moreover, for $\kappa_l < \kappa_g$, note that the revenue of L-CDN first increases as κ_l/κ_g goes far from 1 but decreases from a certain point $(\kappa_l/\kappa_g)^* = 4/7$. The reason is that if L-CDN's quality is too low then eventually no CP would want to use its service.

V. Extensions: Global Know-how and CDNi

We now study the impact of global know-how and the federation on CDN market. Without global know-how, it is easily shown that the revenue of G-CDN (resp. L-CDN) decreases (resp. increases) more rapidly under the federation [18]. However, interestingly, we found that if the traditional CDN has an advantage on global know-how, then the impact of federation on the revenue is significantly different from that without global know-how. The Propositions 3 and 4 illustrate the thresholds for the number of L-CDNs in federation above which the revenue of G-CDN increases and that of L-CDN decreases with the number of federated L-CDNs.

Proposition 3 Under the **HH** condition, if $\mu > 0$, the average revenue of L-CDN (i.e., π_d) decreases in the number of federated L-CDNs, N_d, if

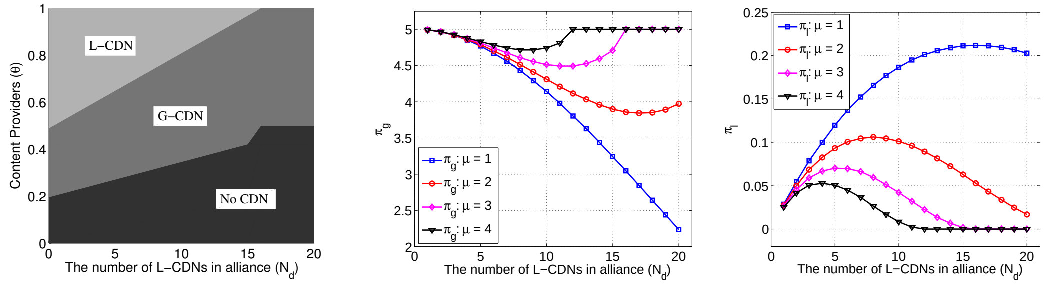
$$N_d > \frac{2\kappa_l N(\kappa_l - \kappa_g)}{3\mu(2\kappa_l - \kappa_g)}. \tag{9}$$

Proposition 4 Under the **HH** condition, if $\mu > 0$, the average revenue of G-CDN (i.e., π_g) increases in the number of federated L-CDNs, N_d, if

$$N_d > \frac{N}{4\mu}\left(\sqrt{\frac{(33\kappa_l^2 - 17\kappa_l\kappa_g + 2\kappa_g^2)(\kappa_l - \kappa_g)}{\kappa_l}} - 3(\kappa_l - \kappa_g)\right). \tag{10}$$

Implications. The proofs are presented in [18]. If *G-CDN has an advantage on global know-how,* for sufficiently large scale of federation, the revenue gain (resp. loss) from global know-how of G-CDN (resp. L-CDN) compensates the revenue loss (resp. gain) induced from the federation (Fig. 5(b), 5(c)). The revenue loss of G-CDN (resp. gain of L-CDN) occurs, since the federation of L-CDNs enlarges the number of service coverage of each L-CDN, but reduces that of G-CDN. For the extreme case, if the G-CDN does not have an advantage on global know-how ($\mu = 0$), the revenue of L-CDN (resp. G-CDN) *linearly* increases (resp. decreases) with the number of federated L-CDNs.

However, with L-CDN's lack of global know-how, there exists a revenue gain of G-CDN (resp. loss of L-CDN), since the disutility of CP from using L-CDN is intensified by the federation. Because of the disutility of CP, the optimal price and market share of L-CDN decrease and those of G-CDN increase with the number of federated L-CDNs. In Fig. 5(a), we depict the market share of each CDN providers with respect to the number of federated L-CDNs. Similarly, the optimal price of L-CDN (resp. G-CDN) linearly decreases (resp. increases), thus the revenue of G-CDN (resp. L-CDN) is convex (resp. concave) with respect to the number of federated L-CDNs (Fig. 5(b), 5(c)). Moreover, for a extremely large alliance, the utility of CP from using L-CDN is zero, then the CP is monopolized by G-CDN. When this happens, the discontinuity of market share occurs and the revenue of L-CDN becomes zero, e.g., if $\mu = 3$, $\theta_l^d = 0$ and $\pi_l^d = 0$ when $N_d \geq 16$.



(a) Market Shares ($\mu = 3$) (b) Revenue of G-CDN ($\mu > 0$) (c) Revenue of L-CDN ($\mu > 0$)

Fig. 5. When G-CDN has a global know-how ($\mu > 0$), revenues and market shares of CDN providers with respect to the number of federated L-CDNs ($\kappa_l = 3, \kappa_g = 1$, and $N = 20$).

VI. Related Work and Conclusion

To the best of our knowledge, there exists only a small number of work on network economics involving CDNs. Hau and Brenner [19] studied the interaction between ISPs and CDNs by considering their pricing decisions, and showed that ISPs have relatively high market power and obtain profits from CDNs to compete for end users. In terms of the relation between CDNs and CPs, Hosanagar et al. [3] addressed the questions on the optimal pricing policies of CDNs. Though CDNs were included in their modeling, the studies in [19] and [3] place CDNs as entities separated from ISPs. Our work handles the case when the roles from ISPs and CDNs are played by a single provider. In terms of ISP-operated CDNs, Cho et al. [20] proposed a content delivery architecture called ISP centric Content Delivery (iCODE) by which an ISP can provide content delivery services as well. They showed that iCODE can offer reduced latency by traffic engineering. Also, in terms of ISP and CP cooperation, Jiang et al. [12] analyzed a case where they jointly optimize the process of server selection and traffic engineering. Moreover, [21] and [22] studied the revenue sharing among cooperative ISPs focusing on the stability of the cooperation and the network-neutrality, respectively. The work of [20] and [12] both focus on the technical aspects whereas our work analyses the economic facets of CDN market in the advent of Telco CDN.

In this paper, we studied the impact of Telco CDN's emergence on the CDN market. The revenue of the total CDN market may *grow*, if Telco CDNs provide sufficiently higher quality content services than the traditional CDN, while both the traditional CDN and the total CDN market lose its revenues, if low quality Telco CDNs enter the CDN market. Moreover, Telco CDNs may want to overcome their limitations on service coverage by the federation with other Telco CDNs. However, *if the traditional CDN has a global know-how,* an excessive enlargement of Telco CDN's service coverage may *decrease* the revenue of L-CDN and *increase* the revenue of the traditional CDN, since the increase of service coverage worsens the disutility of CP from using Telco CDN. For our future work, we would collaborate with the commercial CDNs to obtain the data to estimate the parameters that reflect the actual CDN market.

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