ISP vs. ISP+CDN: Can ISPs in Duopoly Profit by Introducing CDN Services? *

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ABSTRACT
This paper provides an economic analysis of the ISP-operated CDN under a duopolistic competition. The two ISPs are modeled as a platform in a two-sided market providing Internet access to both content providers and consumers. By formulating a 4-level Stackelberg game, we have found that the equilibrium strategy of an ISP in determining whether to launch CDN service depends on the marginal cost of cache server deployment and the two contrary effects: “Competition Effect” and “Delay Reduction Effect.”

Categories and Subject Descriptors
C.2.1 [Network Architecture and Design]: Wireless Communication

General Terms
Design, Economics, Management

1. INTRODUCTION
A content delivery network (CDN) is a large distributed system of servers deployed in multiple data centers in the Internet. The goal of a CDN is to serve content to end users with high availability and high performance [8].

The rapid growth of streaming video traffic [1] incurs large capital expenditures by broadband providers in order to meet the demand and to retain subscribers by delivering sufficiently good quality of experience (QoE) [3]. To address this, Internet service providers (ISPs) have begun to launch their own content delivery networks as a means to lessen demands on the network backbone and to reduce infrastructure investments. As an example, AT&T, in 2011, announced a new CDN service which will enable content to flow directly from its 38 data centers around the world, to reduce transit and latency times [7]. Also, in the same year, BT (British Telecom) unveiled a new service “Content Connect” to offer consumers a better quality video and TV content delivered to their homes even during peak times of congestion [6].

Although there are many CDN providers in the real world, little work has been done in academia on the economics of CDN [2] and, to the best of our knowledge, this study is the first to analyze the optimal behavior of an ISP-operated CDN using game-theoretic models.

2. SYSTEM MODEL
We consider the case of two Internet service providers (ISPs) in competition where only one ISP introduces a CDN service to see whether there exists an incentive to offer CDN. Without loss of generality, we assume ISP1 is the one that introduces a CDN service. Offering a CDN service gives several advantages to every party involved in the content delivery (i.e., ISPs, CPs and consumers) but here we focus mainly on the benefits of deploying cache servers in the ISP’s network which leads to a reduced delay (enhanced response time) for consumers and thus attractive to CPs as well (Fig. 1).

2.1 Utility
2.1.1 Consumer’s Utility
Consumers are distributed in [0, 1] à la Hotelling, where ISP1 is located at 0 and ISP2 at 1. Thus, consumers’ perceived utilities from using each of the ISPs are

\[ u_1^C = v - d_1^C - p_1 - bx \] (1)

\[ u_2^C = v - d_2^C - p_2 - b(1 - x) \] (2)

where, \( v \) is a reservation utility for using either of the ISP’s service, \( d_i^C \) is the consumer’s perceived (expected) delay

\[ a \]

For the full list of Telco CDNs refer to [5]

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*This research was supported by NRF(2011-0002663).

1For the full list of Telco CDNs refer to [5]
when using ISP $i$’s service, $p_i$ is the service price a consumer pays to ISP $i$, and $b$ is the transaction cost.

2.1.2 Content Provider’s Utility

Content providers (CPs) are also distributed in $[0, 1]$, and the utility a CP experiences is similar to the consumer’s utility and is defined as follows:

\[
\begin{align*}
    u_1^P &= w - d_1 - a_i - cx \\
    u_2^P &= w - d_2 - a_i - c(1 - x)
\end{align*}
\]  

(3)

(4)

where, $w$ is a reservation utility for using the ISP’s service, $d_i$ is the CP’s perceived (expected) delay when connecting to ISP $i$’s network, $a_i$ is the service price a CP pays to ISP $i$, and $c$ is the transaction cost. We assume that the reservation utility ($v$ or $w$) is sufficiently high so that both market (Consumer and CP) is fully covered.

2.1.3 ISPs’ payoffs

Finally we consider ISPs’ payoff functions. ISPs obtain a revenue from both consumers and CPs. Also, if an ISP chooses to introduce a CDN it incurs a cost of $\kappa(h)$, where $\kappa(h)$ is an increasing function of $h$, a cache server hit ratio. The payoff experienced by ISP $i$ is given by

\[\pi_i(p_i, a_i, h_i) = p_i t_i + a_i s_i - \kappa(h_i), \quad i \in \{1, 2\}\]

(5)

where $t_i$ and $s_i$ are the market shares of ISP $i$ in the consumer and CP market respectively, and $\sum_i t_i = \sum_i s_i = 1$.

2.2 Delay

We define a delay function as follows:

\[d_i(\tau_i) = \beta_i \tau_i, \quad i \in \{1, 2\}\]

where $\tau_i$ denotes the incoming traffic of ISP $i$’s network and $1/\beta_i$, the capacity of network $i$. Thus, the smaller the network capacity, the higher the delay becomes. Since, for the same given traffic, congestion is higher for smaller network capacity, $\beta_i$ can be interpreted as the network congestion for a constant amount of traffic. Hence, the delay in the network of ISP1 and ISP2 is given by

\[
d_1 = \beta([s_1 t_1 + s_2 t_2] - s_1 t_1) = \beta [t_1(1 - h) + s_1 t_2]
\]

\[
d_2 = \beta(s_2 t_2 + s_2 t_1(1 - h) - s_2 t_2 = \beta [s_2 t_2(1 - h) + t_2].
\]

Since the traffic of CP that is connected to one ISP flows through not only the corresponding ISP’s network but also the opponent ISP’s network, the perceived (expected) delay of both consumers and CPs is affected by the deployment of cache servers of a single ISP. The perceived delay of consumer’s side is given by

\[
d_1^P = d_1 + s_2 d_2 = \beta + \beta t_1[(1 - s_1)^2(1 - h) - h]
\]

\[
d_2^P = d_2 + s_1 d_1 = \beta + \beta(1 - t_1) s_1^2 - \beta t_1 h
\]

and the perceived delay of CP’s side is given by

\[
d_1^P = d_1 + t_2 d_2 = \beta + \beta s_1[(1 - t_2)^2 + t_2(1 - t_1)h] - \beta t_1(2 - t_1)h
\]

\[
d_2^P = d_2 + t_1 d_1 = \beta + \beta t_1[t_1 - (1 + t_1)h] - \beta s_1 t_1(t_1 - h).
\]

3. THE GAME

We formulate a 4-stage Stackelberg game that consists of the following stages:\n
1. CP Pricing Decisions ($a_1$ and $a_2$).
2. CP Connection Decisions: CPs choose the ISPs.
3. Consumer Pricing Decisions ($p_1$ and $p_2$).

The solution concept for this type of game is subgame perfect Nash equilibrium (SPE) and thus we solve it by using backward induction. The equilibrium consumer prices are

\[
p_1^* = b + \frac{2\beta s_1^2 + \beta(1 - s_1)^2(1 - h)}{3}
\]

\[
p_2^* = b + \frac{2\beta s_2^2 + 2\beta(1 - s_2)^2(1 - h)}{3}
\]

and the CP prices are

\[
a_1^* = c + \frac{2\beta t_1 + \beta(1 - t_1)^2 + \beta t_1(1 - 3t_1)h}{3}
\]

\[
a_2^* = c + \frac{2\beta t_2 + \beta(1 - t_2)^2 - \beta t_2(1 - t_2)^2}{3}.
\]

Then, the market share of ISP1 on one side becomes a function of the other as follows:

\[
t_1(s_1) = \frac{1}{3} \cdot \frac{2\beta s_1^2 + \beta(1 - s_1)^2(1 - h) + 3b}{2b + \beta s_1^2 + \beta(1 - s_1)^2(1 - h)}
\]

(6)

\[
s_1(t_1) = \frac{1}{3} \cdot \frac{2\beta t_1 + \beta(1 - t_1)^2 + \beta t_1(1 - 3t_1)h + 3c}{2c + \beta t_1^2 + \beta(1 - t_1)^2 - \beta t_1^2 h}.
\]

(7)

Definition 1. (Equilibrium Market Share) An equilibrium market share is defined as the pair $(t_1^*, s_1^*)$ that satisfies

\[
t_1^* = t_1(s_1^*) \quad \text{and} \quad s_1^* = s_1(t_1^*)
\]

Proposition 1. There exists an equilibrium market share.

Proof. We have

\[
t_1(0) = \frac{1}{3} \cdot \frac{3b + \beta(1 - h)}{2b + \beta(1 - h)} \in (0, 1),
\]

\[
t_1(1) = \frac{1}{3} \cdot \frac{3b + 2\beta}{2b + \beta} \in (0, 1)
\]

and

\[
s_1(0) = \frac{1}{3} \cdot \frac{3c + \beta}{2c + \beta} \in (0, 1),
\]

\[
s_1(1) = \frac{1}{3} \cdot \frac{3c + 2\beta(1 - h)}{2c + \beta(1 - h)} \in (0, 1)
\]

from (6) and (7). Since the functions $t_1(s_1)$ and $s_1(t_1)$ are continuous in $[0, 1]$, there exists at least one equilibrium market share.

□

As a final step, the equilibrium market share is used to obtain the (equilibrium) delay, optimal prices, and profits.

3The timing of the game is predicated on the view that prices for the CPs are set before those of the consumers to reflect the longer time horizon of the contracts between CPs and ISPs as opposed to those of consumers and ISPs [4].

4Although we were not able to prove the uniqueness of the equilibrium market share we have identified the uniqueness by numerical experiment.
In this section, we provide numerical results using the SPE obtained in section 3. Figure 2 shows prices, delays, and (equilibrium) market shares in a less congested network ($\beta = 3$). First, we observe that the delay is reduced as the hit ratio increases and the reduction rate is higher for the ISP introducing CDN. Therefore the prices of the ISP that introduces CDN are larger than that without CDN which naturally leads to higher profit. Also, by the same reason, the market share of ISP+CDN is larger than its opponent.

However, note that both ISPs' profit is lower than the profit when they decided not to introduce CDN (dotted line in Fig. 2(a)) even that of ISP+CDN. This means that if the network is under mild congestion than the ISP who is deciding to launch CDN or not will have no incentive of doing it. To have a comprehensive view of what an ISP’s strategy would look like we plotted a graph (Fig. 3) illustrating the optimal strategy in terms of both congestion ($\beta$) and marginal cost ($k$). From fig. 3 we see that when the congestion is low it is always better not to roll out a CDN service. This means that the “competition effect” is larger than the “delay reduction effect” when the congestion is low. The interpretation is that due to the opponent’s best response to lower the price when the other ISP starts CDN, the price competition occurs and hence the benefit of CDN service, the delay reduction effect, is not sufficient high so as to overcome the competition effect. However, when congestion is high then the delay reduction effect is high enough to win against the competition effect. Once this happens, the ISP’s strategy is determined by the marginal cost of cache server deployment. If it is below a certain threshold, say $k^*(\beta)$, then it is optimal to introduce CDN and, if otherwise, it is better off not to launch CDN.

4. NUMERICAL RESULTS

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5. CONCLUSIONS

In this paper, we have analyzed a duopolistic competition where only one ISP introduces CDN by modeling as a 4-stage Stackelberg game. Our numerical results have shown that the ISP’s choice of launching CDN depends on the parameters such as network congestion$^6$ and cache server cost. Also, we have seen that if the congestion is low then, regardless of the server cost, it is always better off not to roll out CDN service since the benefit of CDN is offset by the competition effect.

6. REFERENCES


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$^5$Here, we assume linear cache server cost, i.e., $\kappa(h) = kh$.

$^6$Since the network congestion can be viewed as the marginal benefit of CDN.