Towards Sustainable Content Delivery with Peer-Assisted CDN

Mohamad Dikshie FAUZIE[†a)]**, Achmad Husni THAMRIN**[†]**, *Nonmembers*, and Jun MURAI**[††]**, *Member***

SUMMARY   Users watched video over Internet has increased and it should be anticipated by ISP. On the other hand ISP want to keep the cost of delivering contents to users is minimize. Due complexity of CDN in term of business and technical, CDN managed ISP/Telco and the initiatives for CDN interconnection are soared in the recent years On the other hand, the deployment of FTTx and xDSL are increasing. We proposed network model of peer-assisted CDN that involving cooperation between ISP/Telco that managed CDN and its customers/users where the peer-assisted application is run on top of customers home gateway. We use a simple stochastic fluid model (stationary and stationary with churn) that seeks the different between ISP/Telco that using CDN only and ISP/Telco that using peer-assisted CDN in delivering video stream. We proposed different admission policy by CDN for peers to join peer-assisted swarms. We do simple techno-economy analysis based on ISP game strategies.

Our simple model can capture the proportional ratio leechers to seeders based on upload rate of seeders for stationary and for stationary with churn. We found that upload rate of seeders has big impact to the systems. Bigger upload means, ISP CDN can minimize cost of delivery to users. Upload rate of seeders has bigger impact compare to discount price
key words: *P2P, CDN, ISP, Game Strategy*

1. Introduction

Streaming contents, especially video, now represent a significant traffic volume on the Internet, and it has become a standard practice to deliver this type of contents using Content Delivery Networks (CDNs), such as Akamai, Limelight for a better scaling and quality of experience to end users. For example, Youtube uses Google cache and MTV uses Akamai in their operations.

With the widespread of broadband Internet access at a reasonable flat monthly rate, users are connected to the Internet 24 hours a day and they can download and share multimedia contents. P2P (peer to peer) applications are also widely deployed and their success is quite important. In China, P2P is very popular; we see many P2P applications from China such as PPLive, PPStream, UUSe, Xunlei, etc. Some news broadcaster are also rely on P2P technology to deliver popular live events. For example, CNN uses Octoshape solution that enable to scale and offer good video quality while the number of users increase.

From Internet provider point of view, the always-on users suggest that it is possible to delegate a portion of com-

puting, storage and networking tasks to the users thus creating P2P networks where users can share files and multimedia contents. Starting from file sharing only protocol, P2P architecture evolved toward video on demand and live events support.

A P2P based architecture usually requires a sufficient number of nodes supplying the data (seeders) to start the distribution process among the joining peers. A peer usually offers a low outbound streaming rate due to the traditional asymmetrical DSL home connectivity and hence multiple peers must jointly stream contents to a requesting peer (leecher) The decentralized, uncoordinated operation implies that scaling to high number of peers comes with side effects. Typical problems of a P2P streaming architecture are low stream quality with undesirable disruptions, resources unfairness due to heterogeneous peer resources and high startup delay. Moreover, current P2P applications are not aware of the underlying network and may conflict with the ISP routing policies and business model.

Nowadays, a number of P2P streaming applications have been designed, analyzed and deployed attracting a significant amount of users. Research studies and deployment experiences have both demonstrated that P2P is a promising solution in terms of scalability and deployment costs. On the other hand, the heterogeneous nature and unstable behavior of the peers contributing bandwidth and computational resources along with the networking issues are limit the commercial success of P2P video streaming applications. Apart from P2P protocols, video contents can be efficiently distributed leveraging on services offered by managed networks architectures and CDN companies. The major issues of CDN are high deployment cost and limited scalability in the long term. Given the complementary features of P2P and CDN, in the last years some hybrid solutions have been proposed [1–3] to take the best of both approaches.

In the recent years, xDSL networks are deployed worldwide and broadband network access helps P2P applications to perform better. In the coming years, FTTH will be massively deployed by network operators in order to offer to their customers and even larger access bandwidth. As access bandwidth increases, P2P systems may become more efficient since a peer can contribute much more.

P2P architecture offers great potential for content providers to cost effectively distribute content by capitalizing network resources of end users. It is economical superiority to the traditional client-server architecture and it has been demonstrated by lots of academic work and successful

commercial systems [3]. We believe more content providers will adopt P2P technology in the future.

In the mentioned work, each end user device is involved directly in the P2P swarm. In such cases, the installation of a P2P software in every end device is necessary and the user itself is directly involved in the content's swarm. In such condition peers may result unstable and the swarm can be affected by rapid and frequent disconnections. Furthermore, user's devices usually can contribute to the swarm with limited upload bandwidth, and techniques developed in P2P to select neighboring peers are often unfriendly with ISP's routing policies. Different topologies have been proposed in literature, where the collaborative mechanism for content distribution is created among more stable devices such as residential gateways which are still geographically close to the end users but directly owned and managed by ISPs. In such conditions, running on more stable and powerful devices, each peer can contribute with more bandwidth to the content swarm compared to the traditional end-user P2P systems. Peer selection procedures can be managed directly by ISP, avoiding the traversal of multiple nodes across ISP boundaries.

In some recent works, the residential gateway (i.e., a home gateway placed in home premise, serving several terminals within the home network but directly managed by ISP) is considered the central entity of such managed P2P infrastructure as describe in [4,5]. Since P2P traffic now decreasing and moving to cloud [6], there is room from ISP to use user's home gateway as peer assisted CDN since users usually do more download rather than upload. The user home gateway is always on 24 hours therefore this is perfect device to run peer assisted application. ISP can give discount price to user's who wants their home gateway to be used as peer assisted by ISP and ISP can get benefit from peer assisted running in their customer home gateway to help their CDN. With the growing interest to do interconnect of CDN [7,8] this architecture can give good benefit for ISP.

In this paper, we study the incentive for adopting peer assisted CDN for streaming purpose and show the advantages to adopt peer assisted CDN.

2. System Description

Figure 2 shows the model of system architecture. That's model offers the opportunity to connect the P2P swarm not directly but through an intermediate later of proxies. This function has potential benefit: boosting download performances (by exposing through proxy devices higher upload bandwidth than end users). It is also increasing privacy by reducing swarm exposure for end users. This two level of CDN follows hierarchical model in Maki et al., [11] with modification.

The first level Level-1 consists high capacity servers strategically placed to increase network backbone capacity. Level-1 is more like current CDN network. In Level-1, CDN node can communicate each other by using common inter-
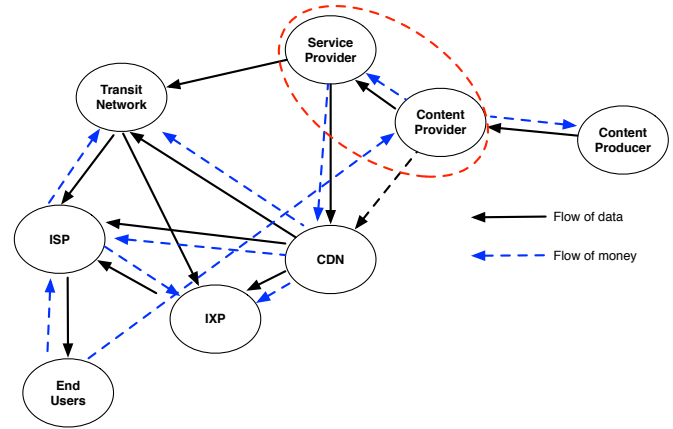

Fig. 1: Complex relationship of entities in Internet. The data flow from content producer to content provider. Content producer such as movies companies send their movies to content provider for example: Netflix and Hulu. Content providers then deliver the movies using CDN or they also can use their upstream provider. Depends on routing and peering policy, data from CDN can flow directly to ISP or flow to ISP via IXP (Internet Exchange) or via transit network. Flow of data noted by straight arrow and flow of money noted by dash arrow line. In current modern Internet topology, content provider and service provider can be merged in on entity, for example: Google. Labovitz et al., [6] mentioned that the hyper-giant entities such as Google doing massive peering to IXP in order to be closed to ISP. Although CDN is placed close to ISP network, it does not guarantee end-users can get good quality video stream [9]. Other than technical complexity as mentioned before, CDN also faces economic complexity [10]. Therefore, the future of CDN business is likely to live deeper into ISP networks, more integrated into and interleaved with ISP infrastructures.

connect interface even though the CDN node are owned by different companies or different ISPs [7].

Level-0 consists CDN proxies are owned or to be managed by ISP. For big ISP different CDN proxies in level-0 can be put at different cities or different geographically areas. These nodes are placed closer to end users. CDN proxies can communicate each other to react to the content requests from users. Level-0 are the natural service points for the users and they can offer the best quality of service if the are able to efficiently cache the requested content. The state of the Level-0 and Level-1 caches is stored in DHT. The DHT is used to keep an updated record for each content in scalable manner. This different caching levels are used to offer an adaptive, flexible, and scalable service to the users.

We noted that CDN proxy has a limited capacity and it may not be able to satisfy all clients. A peer-assisted CDN introduced peer coordination mechanism into CDN system. In this case CDN proxy is responsible to make peer coordination. For any new streaming request, the CDN proxy will have to make two decisions. The CDN proxy will make a arrival node as seeder or as leecher based on adaptation strategy or a capacity constraint. In this system, we define a seeder is a node or a peer that receive stream from CDN proxy and a leecher is a node or a peer that receive stream from a seeder. To maintain low delay and good quality video streaming, seeder only receive stream directly from CDN

proxy and leecher only receive from seeders.

It is very important for ISP to make sure CDN proxy capacity is enough while maintaining minimum capacity requirement. Although peer selection strategy is out of scope of this paper, we assume that peers form random mesh networks. In the next sections we will show how CDN proxy can make such decision in a way to optimize system.

3. System Model and Analysis

We present a model between P2P and CDN using simple a single bitrate for video streaming as shown in Fig.3. The model is a stochastic fluid model similar to [12]. While the authors in [12] focus on probability of degraded service on small and large systems, our work focus on minimum capacity or of CDN proxy to support the system. Minimum capacity is very important to ISP for capacity planning. On next subsection we also present a model of simple game theory between ISP who operate P2P-CDN and users. We aim to find out the indifferent utility function between ISP and users.

3.1 System in Stationary State

Let the number of leechers and the number of seeders in the P2P swarm, not including the CDN proxy, as n_l and n_s, and the bitrate as r. In order to satisfy the users for a streaming content, the minimum total upload bitrate to the P2P swarm is $(n_s + n_l)r$. Let the upload capacity of each seeder as u_s, $0 \leq u_s \leq 1$, therefore the minimum CDN proxy capacity to
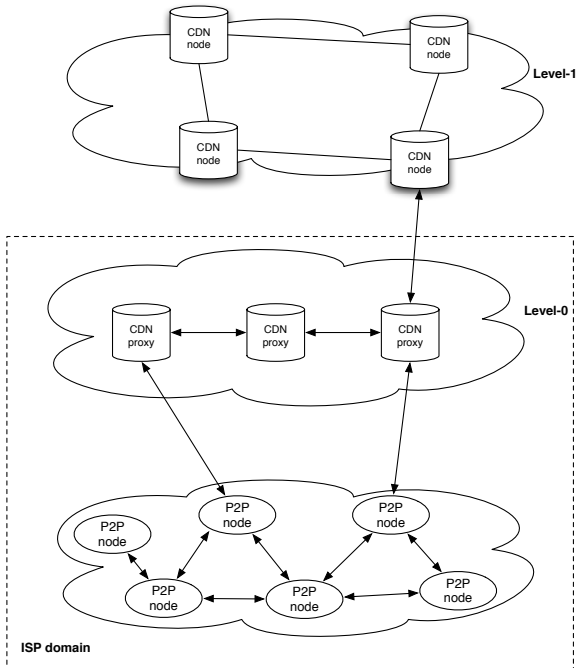

Fig. 2: Two tier CDN-P2P topology. The CDN proxy maintained by ISP. ISP also has CDN node. CDN node can exchange contents with other CDN node owned by other CDN companies. P2P nodes are ISP's customers that run P2P software.
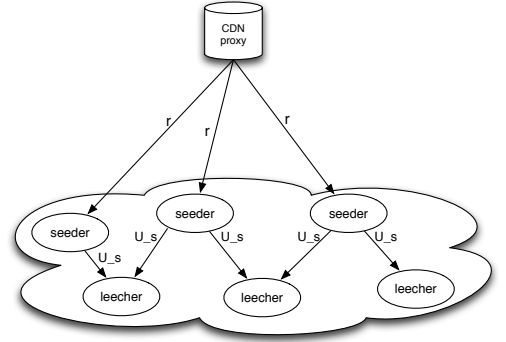

Fig. 3: System architecture on L0. P2P nodes that run on user home gateway communicates to CDN proxy.

support the system is:

$$U_p = n_s.r + n_l.r - min(n_s.u_s.r, n_l.r). \qquad (1)$$

Note that if $n_l.r$ is less than the upload capacity of the seeders, the proxy does not need to serve the leechers. Also note that if the system is for file sharing, then the CDN proxy does not need to serve the seeders. From the above equation, we define $X = \frac{n_l}{n_s}$, which is the ratio of the number of leechers to the number of seeders, and we normalize $r = 1$, hence:

$$\frac{U_p}{n_s} = (1 + X - min(u_s, X)), \qquad (2)$$

which means that the upload capacity requirement of CDN proxy relative to the number of seeders will be higher as X increases beyond $X = u_s$.
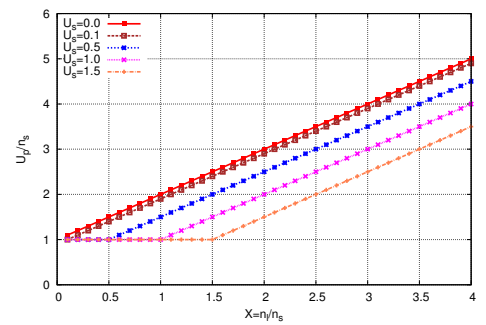

Fig. 4: System in stationary state.

Figure 4 shows the system in stationary state. For $u_s = 1.5$, the minimum required capacity CDN proxy relative to the number of seeders to support the system can be achieved if the ratio of leechers to seeders is less than 1.5. We see that the CDN proxy prefers a higher u_s in the system. A special case is $u_s = 0$, which is equivalent to no P2P swarm. It is also clear that as X increases, the CDN proxy must add its capacity, thus adding the cost for the ISP.
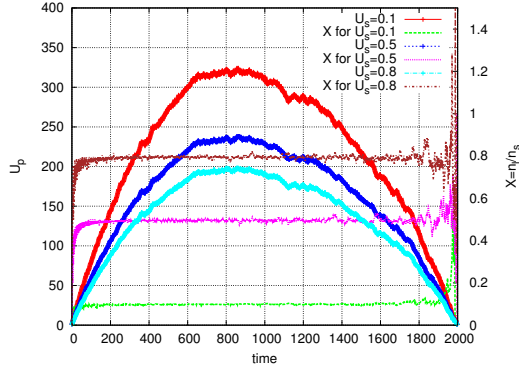
Fig. 5: U_p for $N = 1000$ for admission policy 1.
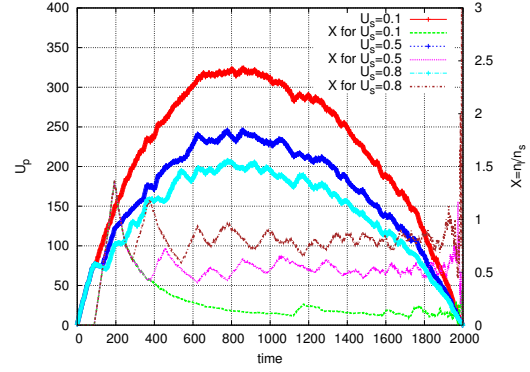
Fig. 6: U_p for $N = 1000$ for admission policy 2.

3.2 System with Churn

In this analysis, we assume peers (user nodes) join at random times, stay in the system for random period of time, then leave. We assume the peer arrivals follow a poisson process with rate λ, and peers stay in the system follow a general probability distribution with mean $\frac{1}{\gamma}$. Let $N(t)$ be the number of peers in the system at time t, i.e., the number of nodes in a $M/G/\infty$ queue, thus we can denote U_p as a function of time t

$$U_p(t) = N(t)r - min(n_s(t)u_s r, (N(t) - n_s(t))r), \quad (3)$$

where $N(t) = n_s(t) + n_l(t)$, and $n_s(t)$ is determined by the system's admission policy.

We now compare two admission policies: 1. the system starts admitting new arrivals as seeders until $(n_s.u_s > n_l)$, then each arrival is admitted as a seeder or a leecher according to the equation. 2. the system admit arrivals every d time interval. If $(n_s.u_s > n_l)$ at the beginning of a time interval, all arrivals within the time interval are admitted as leecher, otherwise as seeders.

Figure 5 shows the U_p values during simulation with $N = 1000, \lambda = 2, \mu = 2, u_s = \{0.1, 0.5, 0.8\}$, and we use the first admission policy in this simulation. We also plot ratio values X on the second Y-axis. Figure 6 shows the U_p values during simulation using the second admission policy with $delta_t = 1.0$ and other parameters are kept unchanged. From both figures, we can see that the first admission policy can stabilize the value X in order to keep the CDN proxy capacity enough to supply the system. In the second admission policy, CDN proxy decides the same role for peers arriving in a time interval. Figure 7 shows the CDF of X for $U_s = 0.1, U_s = 0.5$, and $U_s = 0.8$ for both admission policies. We can see that second admission policy gives a higher variance, while first admission can keep the ratio ideal. Finally, we can see that seeder upload has a good contribution to this system. The next section discusses how to give incentives to the peers in this system.

3.3 ISP Strategies: Game Theory Approach

In this section, we present simple game theory approach for analysis of ISP strategies. Game theory as described in [13] is a mathematical framework to study and analysis of situation where decisions made by a set of two or more rational players. Basic element of game are: rational players, strategies, and payoff or utility. Rational players choose a strategy for maximizing its payoff or utility. Extensive-form game is representation of corresponding decision nodes in a directed tree. Later, we will use extensive-form game to represent our game. In our model, ISP has already attempted to implement solution for peer-assisted CDN. Moreover, it is reasonable to assume that ISP is naturally initiators. Stackelberg game also known as a leader-follower game is a class of game that concerns with situation where one player, the leader, initiates the decision making and where the second player, the follower, responds to the actions by the leader. Moreover in our model, ISP can be modeled as leader who decided to implement peer-assisted or not according to their expected payoff, while users can be modeled as followers that evaluate the decision of the ISP and responds according to their available actions and payoffs. In this section, we will focus on ISP side.
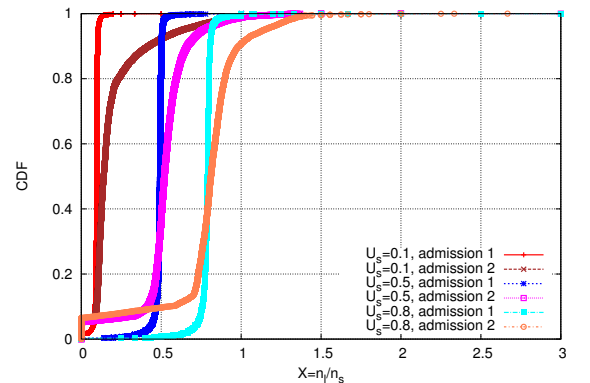
Fig. 7: CDF of n_l/n_s. We can see that the variance is higher for admission policy 2 compared to the admission policy 1.
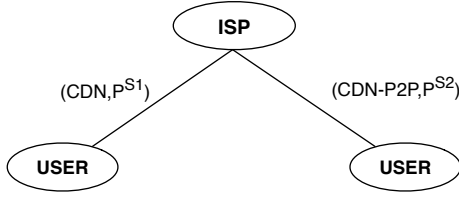
Fig. 8: Extensive form of game between ISP's strategies

Definition 1 (ISP Strategies): We define the pure strategy space S_{isp} to include two strategies combination choice $s \in \{CDN, CDN - P2P\}$ and corresponding subscription free P^s. Futhermore, we denote the strategies as:

- $s_1 = (CDN, P^{s_1})$: the ISP decides to use CDN only and thus keeps charging the initial subscription free P^{s_1}.
- $s_2 = (CDN - P2P, P^{s_2})$: the ISP decides recommends peer-assisted and offers a subscription fee $P^{s_2} \leq P^{s_1}$.

Where the ISP strategy space $S_{isp} = \{s_1, s_2\}$.

3.3.1 ISP Payoff

We now describe the payoff function for ISP in our model. We assume a profit maximizing ISP that gains higher utility in proportion to the increasing profit, which is only determined by the revenue from users and the bandwidth cost to reach the users.

For the revenue model, we assume that the ISP collects revenue solely by charging an initial flat rate subscription fee $P^{(s_1)}$ to its N number of users who purchase internet access with equal and fixed quality of service. ISPs are often price discriminatory towards its customers and thus operate with different price levels for different bandwidth or QoS. ISPs are often get revenue from other businesses such as email hosting, web hosting, etc. In our model, we do not include such revenue, and we found it reasonable only to focus on users that buy the same internet access product. Given the above simplifications, the ISP collects a total revenue (when deciding on a strategy s) of $R = NP^{(s)}$. The analysis focuses on the ISP side only, and we are very interested to see the difference (δ) between payoff of strategy s_1 and strategy s_2. For strategy s_1, the payoff for the ISP is:

$$\pi_{(N)}^{(s_1)} = \pi_{(n_s)}^{(s_1)} \tag{4}$$

$$= n_l P^{(s_1)} - n_l T P_t \tag{5}$$

note that in strategy s_1 we assume all peers get stream from CDN thus all peers are seeder.

For strategy s_2, ISP has payoff:

$$\pi_{(N)}^{(s_2)} = \pi_{(n_l)}^{(s_2)} + \pi_{(n_s)}^{(s_2)} \tag{6}$$

$$= n_l p^{(s_1)} - n_l T P_t + max(n_s u_s, n_l) T P_t$$
$$+ n_s P^{(s_2)} - n_s T P_t \tag{7}$$

note that in $n_l p^{(s_1)}$ we use $p^{(s_1)}$ because leechers are not join

to peer-assisted mode offer by ISP thus the price is without discount.

Therefore payoff difference between strategy s_1 and s_2 is:

$$\delta = n_l P^{(s_1)} - n_l T P_t \tag{8}$$

$$- n_l p^{(s_1)} - n_l T P_t + max(n_s u_s, n_l) T P_t \tag{9}$$

$$+ n_s P^{(s_2)} - n_s T P_t \tag{10}$$

Description of notation as follows:

- n_s is number of seeders.
- n_l is number of leechers.
- $P^{(s_1)}$ is subscription fee for strategy s_1
- $P^{(s_2)}$ is subscription fee for strategy s_2 where it is discount price.
- T is video traffic bitrate.
- P_t is transport cost.
- U_s is upload rate of seeders.
- τ^{s_1} is traffic cost for strategy $s^{(s_1)}$.
- τ^{s_2} is traffic cost for strategy $s^{(s_2)}$.

Explanation of notation as follows: $n_l.P^{s_1}$ is ISP revenue and $max((T.P_t.n_l - n_s.u_s.T.P_t), 0)$ is ISP traffic cost.

The traffic cost $\pi_{(n_l|n_s)}^{(s_1)}$ is depends on threshold value n_l/n_s that we discussed in Sec.3.2. If $n_s.u_s > n_l$ then bandwidth cost is minimum because ISP does not need to add seeders, instead leecher can be added to the system. If $n_s.u_s < n_l$ then the bandwidth cost is maximum because ISP need to add seeders. The maximum of difference between these value and 0 is the cost of ISP traffic. We also noted that $P^{(s_2)}$ is price that ISP give in strategy s_2. $P^{(s_2)}$ is discount price because users accept strategy s_2 to join peer-assisted CDN. We can get discount price by indifference payoff between strategy s_1 and s_2 with total peer N:

$$\pi_{(N)}^{(s_1)} = \pi_{(N)}^{(s_2)} \tag{11}$$

$$N.P^{(s_1)} - \tau^{(s_1)} = N.P^{(s_2)} - \tau^{(s_2)} \tag{12}$$

$$P^{(s_2)} = P^{(s_1)} - \frac{1}{N}(\tau^{(s_1)} - \tau^{(s_2)}) \tag{13}$$

Where $\tau^{(s_2)} = n_s.T.P_t$ is traffic cost for strategy s_2. Factor $\frac{1}{N}(\tau^{(s_1)} - \tau^{(s_2)})$ is discount factor. We can define discount factor as $\frac{\gamma}{N}(\tau^{(s_1)} - \tau^{(s_2)})$. Maximum discount that ISP can give to user when $\gamma = 1$ and minimum discount that ISP can give to user when $\gamma = 0$. We can also say that γ is a ratio that express how much of the ISP expected utility increase it wants to share with its users.

3.3.2 Numerical Result

In this subsection we do numerical evaluation the ISP strategy. The assumptions that we use for this numerical simulation:

- We assume that traffic is generated by video traffic and the traffic.
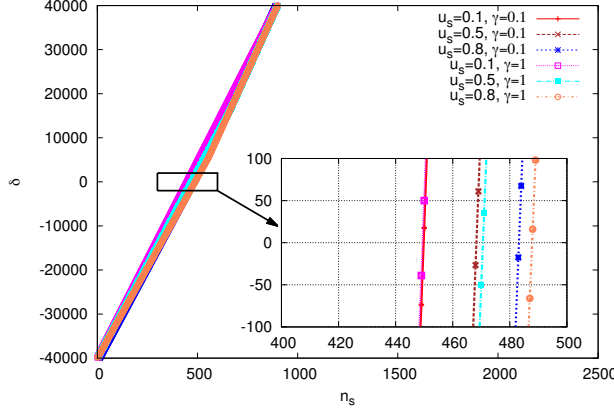- We assume that user utilize 100% of their internet connection capacity.

Fig. 9: δ between strategy s_1 and s_2 with U_s variation and γ variation.The intersection of lines with x-axis = 0 is the point where ISP has minimum payoff with maximum number of seeders.

- We assume users never turn off their home gateway so ISP do not need to give penalty to users.
- We assume there is no investment cost though ISP may need to give different firmware software to run peer-assisted application inside users home gateway. We assume that cost is very small thus we assume investment cost is zero.

Parameters value that we use in this numerical simulation as follows:

Table 1: Parameters values for simulation

u_s	$\{0.1, 0.5, 0.8\}$
N	1000
T	1Mbps
P_t	10USD
$P^{(s_1)}$	50USD
γ	$\{0.1, 1.0\}$

Figure 9 shows difference payoff between strategy s_1 and s_2. The intersection between lines and x-axis=0 is the point where ISP has minimum payoff with maximum number of seeders. for $u_s = 0.1, \gamma = 0.1$ maximum number of seeders is 449. for $u_s = 0.1, \gamma = 1$ maximum number of seeders is 450. for $u_s = 0.5, \gamma = 0.1$ maximum number of seeders is 469. for $u_s = 0.5, \gamma = 1$ maximum number of seeders is 471. for $u_s = 0.8, \gamma = 0.1$ maximum number of seeders is 484. for $u_s = 0.8, \gamma = 1$ maximum number of seeders is 488. if we compare same γ for different u_s the different minimum seeders is large. if we compare same u_s for different γ the different minimum seeders is small. Therefore, we can see that u_s factor is dominance over γ factor.

4. Related Work

Content Distribution Networks with peer-assisted have been successfully deployed on the Internet, such as Akamai [1] and LiveSky [14]. The Authors of [1] conclude from two real world traces that hybrid CDN-P2P can significantly reduce the cost of content distribution and can scale to cope with exponential growth of Internet video content. Yin et al., [14] described commercial operation of CDN with peer-assisted in China. LiveSky solved several challenges in the system design such as dynamic resource scaling of P2P, low startup latency, ease of P2P integration with the existing CDN infrastructure, and network friendliness and upload fairness in the P2P operation. Xu et al., [15] using game theory shows that right cooperative profit distribution of P2P can help ISP to maximize the utility. Their model can easily implemented to current Internet economic settlement. Misra et al., [4] also mentioned the importance of P2P architecture to support content delivery networks. The author uses cooperative game theory to formulate simple compensation rules for users who run P2P to support content delivery networks.

The idea of telco or ISP managed CDN has been proposed in recent years. The complexity of CDN business makes telco and ISP want to managed their own CDN. It has been shown that it is cost effective [16] [17]. Kamiyama et al., [18] proposed optimally ISP operated CDN. Kamiyama et al., mentioned that to deliver large and rich Internet content to users, ISP needs to put their CDN in data center. The locations are limited while the storage is large, makes this solution become effective, using optimum placement algorithm based on real ISP network topologies. The authors found that inserting CDN to ISP's ladder-type networks is effective to reduce the hops length thus reduce total link cost. On the other hand, an effort for telco or ISP managed CDN to be connected each other has been also initiated by Cisco to form CDN federation [16] using open standard [7]. They argue that the current CDN architecture is not close enough to the users and ISP can fill this position.

The idea to utilize user's computation power to support ISP operation is not new. The Figaro project [19] proposed residential gateway as an integrator of different networks and services and become Internet-wide distributed content management for future Internet architecture [19]. Cha, et al., [5] performed trace analysis and found that IPTV architecture powered by P2P can handle much larger number of channels with limited demand for infrastructure compare to IP multicast. Jiang et al., [20] proposed scalable and adaptive for content replication and request routing for CDN servers that located in users home gateway. Maki et al., [11] propose traffic engineering for peer-assisted CDN to control the behavior of clients and presents a solution for optimizing the selection of content files. Our work is same in system model architecture which uses different level of topologies (Level-0 and Level-1), where in Maki et al., [11] the authors use different names, which are local domain and global domain. While our work focus on fluid limit for the number of peers needed to support video stream bitrate in single bitrate system and modeling simple economic incentive for ISP, Maki et al., [11] focuses on traffic engineering algorithm for optimizing the selection of content files and controlling the behavior of clients.

5. Conclusion and Future Work

This paper presents scheme for peer-assisted ISP managed CDN model that estimate lower bound of peers based on stochastic fluid model and estimate the economic incentive for ISP based on game theory. We found that upload rate seeder has big influence to the system. This is same observation as [15] Our numerical result shows that peer-assisted CDN managed by ISP or telco is feasible to deploy and does not harm to ISP business. Our future work will include energy efficient trade off this peer-assisted ISP managed CDN. We are very interested to know how much energy saving by ISP and how much increase of energy at users home gateway side in this architecture.

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Mohamad Dikshie Fauzie was born in 1976. He received a bachelors degree and a master's degree from Institute of Technology Bandung, Indonesia. He is currently a Ph.D candidate at Keio University's Shonan Fujisawa Campus.

Achmad Husni Thamrin is Assistant Professor at Keio University. He is a graduate of Keio University, Graduate School of Media and Governance (Ph.D 2005, MMG, 2002). His research interests include multicast, Internet over broadcast media, and peer-to-peer networks.

Jun Murai was born in March 1955 in Tokyo. Graduated Keio University in 1979, Department of Mathematics, Faculty of Science and Technology. He received his M.S. for Computer Science from Keio University in 1981, and received his Ph.D. in Computer Science, Keio University in 1987. He specializes in computer science, computer network, and computer communication. He is currently Dean of the Faculty of Environment and Information Studies, Keio University since October 2009. Former Vice-President of Keio University from May 2005 to May 2009. He was an Executive Director of the Keio Research Institute at SFC, Keio University from 1999 to 2005.