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Envy-Free Resource Allocation and Request Routing in Hybrid CDN–P2P Networks

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Abstract Hybrid CDN–P2P networks (HCDNs) combine Peer to Peer (P2P) networks and Content Delivery Networks (CDN) to benefit from their complementary advantages. In order to enable a traditional CDN to offer hybrid content delivery service, we introduce a resource scheduling mechanism to perform the request routing process and determine the desired level of contribution for users. The proposed mechanism relies on a truthful, profit maximizing, envy-free auction to optimize contributions of the end-users in P2P content delivery. Based on the proposed solution, economics of content delivery in the HCDN are studied and it is shown that through our resource scheduling mechanism, it is possible to serve a big fraction of end-users with higher quality content, increase the net profit of the HCDN provider, and decrease expenditures of the content provider simultaneously.

Keywords Hybrid CDN–P2P network · Economic mechanism design · Resource scheduling · Request routing · Auction

1 Introduction

Hybrid CDN–P2P networks (HCDN) benefit from the complementary advantages of Content Delivery Networks (CDN) and Peer-to-Peer (P2P) technologies to offer low-priced, scalable, high-quality, and reliable services. In HCDNs, users have the option to choose either a base quality Client–Server (CS) or the better quality hybrid (Hybrid) modes to receive the content [1], Fig. 1. In the hybrid mode, users have to

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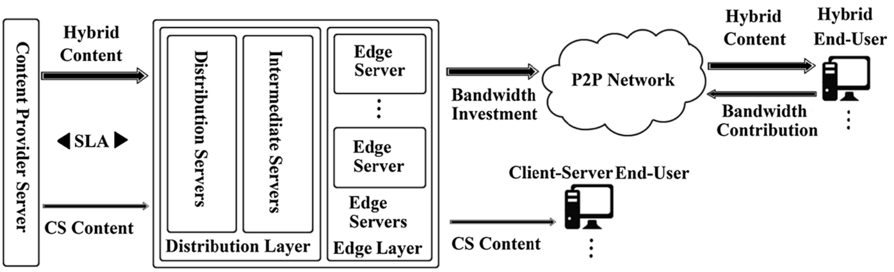

Fig. 1 Hybrid and Client–Server content delivery approaches in HCDNs (thickness of *arrows* symbolize traffic intensity)

contribute their upload bandwidth in P2P content delivery to receive a higher quality of service.

In HCDNs, similar to CDNs, the content provider pays the costs of the content delivery service, based on the Service Level Agreement (SLA) contracted between the (H)CDN and content provider. If the user opts to receive the higher quality content in the hybrid mode, both content provider and end-user pay for content distribution costs. In this case, the content provider pays the content delivery costs agreed on in the SLA, while the end-user must afford a fraction of the content delivery costs, by contributing its available upload bandwidth into the hybrid content delivery process. Therefore, in order to incentivize end-users to contribute in the content delivery, the hybrid service must be offered with a better quality compared to a CS service [1]. Additionally, the price of hybrid service at the SLA must be kept less than the CS service to convince the content provider to request hybrid content delivery.

Conventional CDNs optimize their performance relying on two key mechanisms: Replica Placement (RP) and Request Routing (RR) [2, 3]. An RP mechanism determines the placement of replicas while RR receives the outcome of the RP mechanism and redirects the users to the appropriate edge server. Most existing CDNs rely on Domain Name Service (DNS) as the foundation of their RR mechanism. Relying on a simple and convenient DNS-based RR mechanism, CDNs are able to minimize their content delivery costs [4, 5] and balance the load on their edge servers economically. A DNS-based RR mechanism replies to each RR request, with a list of nearby available edge servers.

In HCDNs, the RR mechanism involves three correlated decisions in response to each request. *First*, among geographically close edge servers, which server(s) must take the responsibility of serving the requesting end-user? *Second*, which service mode (P2P or CS) must be used to deliver the service to the end-user? And *third,* how much in resources do the end-users have to contribute to receive the content in the hybrid mode?

HCDNs have a complex economic cycle. Therefore, designing an RR mechanism for them requires considering new aspects. *First*, in HCDN, the hybrid content delivery approach can decrease bandwidth consumption and increase the net profit of the HCDN provider. The sole economic objective of the RR mechanism in traditional CDNs is to minimize the content distribution costs. In HCDNs, the diverse bandwidth contribution of the end-users and different prices of the service modes (in the SLA) changes the economic model of the system. Therefore, while designing an RR mechanism for HCDNs, both cost and revenue of the system must be taken into account. *Second*, the edge servers spend two types of bandwidth to serve hybrid end-users; their dedicated bandwidth and the bandwidth contributed by the end-users. These servers buy the bandwidth contributed by the end-users at the cost of spending a reasonable amount of their dedicated bandwidth. Consequently, both types of available bandwidth have economic value for them. The price of the bandwidth varies from server to server. Therefore, it is crucial to select the most economic edge server to deliver the content to the end-user. *Last but not the least*, the RR mechanism, in addition to determining the IP address of the best server, must determine the quantity of the upload bandwidth contribution of the users interested in receiving the content in hybrid mode. In P2P networks, the bandwidth allocation problem is a key challenge [6]. Feldman and Chuang [7] addressed the selfish behavior of peers and introduce a spectrum of solutions to the free-riding[1] problem. Ramayya et al. [8] showed that the free-riding problem can decrease the throughput of the P2P network dramatically. They also revealed that the unbalanced and high variance upload contribution of peers can cause several challenges including poor reliability and low end-user satisfaction [9]. It is crucial for the designer of the resource allocation mechanism to develop a coherent policy to motivate the end-users to contribute maximally in the P2P content delivery. Therefore, the RR mechanism must prevent free riding. It also is needed to benefit fairly from the bandwidth contribution of end-users.

In our previous work, we introduced a profit maximization RR mechanism for HCDNs [10]. That work suffers from some technical limitations. First, it demanded prior knowledge of statistical distribution of parameters of the network end-users. Second, it prevented free riding but it was not envy-free.[2] Therefore, in the mechanism introduced in the previous work, like many other P2P networks [9], a small fraction of peers provided a big fraction of the total P2P bandwidth contribution. Due to the former limitations, the mechanism required tuning by the administrator and the latter imperfection affected both user satisfaction and reliability of the P2P network.

In this paper, relying on an *envy-free, prior-free, economic resource scheduling mechanism,* we remove limitations of the previous RR mechanism. The aim of the mechanism is to enable a commercial traditional CDN to offer hybrid content delivery services. The mechanism relies on the economic modeling of the HCDN and end-users, and considers the net profit of the HCDN provider as the objective. The proposed RR mechanism relies on the cooperation of the edge servers, a traditional DNS based RR mechanism and a Hybrid Request Scheduling Server (HRSS). The proposed mechanism relies on the communication of a few small messages to determine the quantity of production and price of the hybrid service at

[1] The situation in which peers are consuming resources without fair contribution of their resources.

[2] The situation in which no customer has an incentive to dispute the allocation. In the economics literature, the notion of envy-freeness was used to model fair equilibrium pricing in various settings.

each edge server. The price and production quantity of each edge server in this domain are equivalent to the required contribution of the hybrid end-users in the form of upload bandwidth and the way they are clustered between the CS and hybrid content delivery modes.

The major contribution of this paper is an envy-free profit-maximizing economic mechanism for request routing and resource allocation in HCDNs. This approach extends the RR of traditional CDNs enabling them to offer hybrid streaming content services. Our proposed mechanism obeys the SLA, increases the net profit of the HCDN service provider, improves the upload contribution of the end-users and preserves the fairness among the P2P end-users. Moreover, it is able to integrate into existing popular DNS-based RR mechanisms, and specifically, it does not require tuning any parameters by the CDN administrator.

The remainder of this paper is organized as follows: related works and neighboring problems are explored in Sect. 2. In Sect. 3, the problem of Economic RR in Hybrid CDN–P2P networks is introduced formally. Section 4 is devoted to the formal description of the RR problem. Section 5 introduces the proposed mechanism. The proposed mechanism is evaluated in Sect. 6. Finally, we conclude in Sect. 7.

2 Related Work

The potential of HCDNs were studied experimentally by Yin et al. [1]. Huang et al. [11] reported theoretical studies of HCDNs. Ha et al. [12] compared processing and storage costs in CDNs, P2P networks, and HCDNs. Hai et al. [13] presented a performance modeling study of HCDNs. Also, a comparative study of bandwidth consumption in CDNs and Hybrid CDN–P2P networks is presented by Huang et al. [11]. These studies showed that application of HCDNs can decrease the bandwidth consumption of a content delivery system, deliver high QoS to the end-users and decrease the expenditures of the CDN provider.

ZhiHui et al. [14] surveyed Hybrid CDN–P2P networks and classified them into two major groups. In the first class, [15, 16], and [17], the architecture of the HCDN is inspired by the P2P systems and the CDN part is employed to retransmit the missing blocks of the playback buffer. Chao et al. [18] introduced a resource scheduling mechanism for this class of networks. A second class of Hybrid CDN–P2P architectures was inspired from CDNs. They are able to be deployed as a commercial Hybrid CDN–P2P network and can extend existing commercial CDNs. Relying on the CDN infrastructure, these networks are able tolerate the fact that some end-users might not prefer to install the special P2P content distribution application software on their machines [1]. The architecture employed in the second class is able to serve the end-users directly from their CDN architecture. Therefore, for end-users it is not mandatory to install the specialized application software. However, end-users equipped with this special P2P client software are able to receive the content in higher quality [19]. LiveSky [1] can be referred to as one of these architectures and also as the first successful deployment of Hybrid CDN–P2P networks. LiveSky extends an old fashioned CDN to a Hybrid CDN–P2P network and has succeeded to serve 10 million concurrent requests for streaming videos.

Traditional CDNs employ RR and RP mechanisms to optimize their performance [2]. Keymasi and Analuoi [20] and Zhan et al. [21] presented some RP mechanisms for HCDNs. While the RP mechanism decides both placement and the number of replicas, the RR mechanism of the HCDN (in addition to assigning end-users and edge servers) is needed to incentivize end-users and try to improve their contribution on P2P content delivery. Although there are several implementations and studies in the field of Hybrid CDN–P2P networks, to the best of our knowledge, there is no work on the economics of request routing and resource allocation mechanisms in Hybrid CDN–P2P networks. This work might be the first.

Owing to the complex economic model of HCDNs [12], their RR and resource scheduling mechanisms must consider the economics of HCDNs systematically. Therefore, we rely on two economic models to select the most beneficial assignment of the end-user and edge servers and to maximize the contribution of the end-users in hybrid content delivery. In this paper, we extend the traditional DNS-based RR mechanism to enable hybrid content delivery in CDNs. Despite shortcomings of the DNS-based RR [4], most of the popular existing CDNs, e.g., Akamai, employ this mechanism because of its ease of management, scalability, and simplicity [2].

P2P networks and their challenges are studied in a wide spectrum of studies. Buford et al. [22] presented an in-depth survey on P2P networks, their challenges, and applications. Nowadays, almost all the challenges of P2P content delivery including routing, overlay network maintenance (churning problem), fault tolerance, and indexing issues (data localization) are solved. The HCDN architecture relies on P2P content delivery at its edge layer. The only difference of the P2P layer of HCDNs with traditional P2P systems remains in their economic objective. Garmehi and Analoui in [23] introduced a scalable mechanism for constructing and maintaining the multicasting trees in HCDNs. In this paper, the challenges of P2P content delivery fall outside the scope of this study and it is assumed that the HCDN employs compatible techniques available in the P2P industry.

In P2P networks, the end-users behave selfishly and prefer to minimize their contributions to the P2P content delivery. A lack of coherent incentive policies to overcome selfishness of peers, results in a free-riding problem. Free-riders benefit from the resources of the P2P network but do not contribute their resources into the content delivery process. In this research, we have embedded an auction-based resource allocation mechanism [24] into the request routing mechanism of the HCDN to make it possible to interface a traditional CDN with the P2P network.

In HCDNs the RR mechanism, in addition to assigning the end-users to the edge servers, must optimize the contributions of the end-users in hybrid content delivery. Bandwidth discovery and allocation in traditional P2P overlay networks is a well-known problem in computer networks literature [25, 26]. Due to the high potential of economic mechanisms and game theory, many of the works in this domain rely on auctions and incentivizing peers [27]. In game theory [28], truthful auctions are divided to two classes: (1) mechanisms relying on truthful auctions and implementing social choice functions, e.g., VCG and Vickrey auctions; (2) truthful profit maximization auctions. Due to the economic model of traditional P2P networks, mechanisms of the first group are applied widely [29] in this domain. While VCG auctions suffer from several limitations in practice [30], the most successful mechanism in this group of mechanisms is Vickrey second price auction [31, 32]. In this work, features of the problem are shown to be more compatible with one of the mechanisms classified in the second group [24]. There are two categories of profit maximizing auctions: the Bayesian approach and Priori-free approximation. The Myerson approach [28] belongs to the first category and is proved to be able to maximize the net profit of the digital good auction when distribution of the private value of buyers comes from a previously known i.i.d.[3] statistical distribution [33]. Our previous study on resource scheduling mechanisms in HCDNs [10] is based on this approach. Although it demands knowing the statistical distribution of private values of the end-users, it is shown to have perfect microeconomic performance. In this study, we are about to embed the priori-free approximate approach in the RR and resource scheduling mechanisms [34].

In the literature of the economic mechanism design theory, most of the profit-maximizing auctions are usually verified against VCG and Vickrey auctions [35]. Additionally, in a previous study [10], we employed the Myerson mechanism to perform the request routing and resource allocation of HCDNs. Therefore, in this study, we compared the performance of the proposed mechanism with VCG, Vickrey, and Myerson mechanisms to show its advantages over these mechanisms.

3 Problem Statement

In order to introduce the problem formally, we need to define the underlying HCDN infrastructure, establish the economic model of the system, model the end-user's behavior and formalize the mathematical definition of the resource allocation and request routing mechanism.

3.1 Architecture

A Hybrid CDN–P2P network receives the content from the content provider and delivers it to the end-users. In this network the content provider contracts an SLA with the HCDN provider and provides distribution servers with the flow of the content. The content is multicast through intermediate servers and replicated on edge servers selected by the RP mechanism [36]. In this way the architecture illustrated in Fig. 2 is employed as the underlying network of the HCDN.

The RP mechanism provides the RR system with the list of edge servers containing replicas of the content. Users progressively send their requests to the RR mechanism, one by one. The RR mechanism must provide each user with the address of a suitable server containing a replica of the content. If the user prefers to receive the content in the hybrid mode, the RR mechanism and the user must reach an agreement on the amount of upload bandwidth the user must provide in return of the high quality P2P service, Fig. 3.

[3] Independent and Identically Distributed.

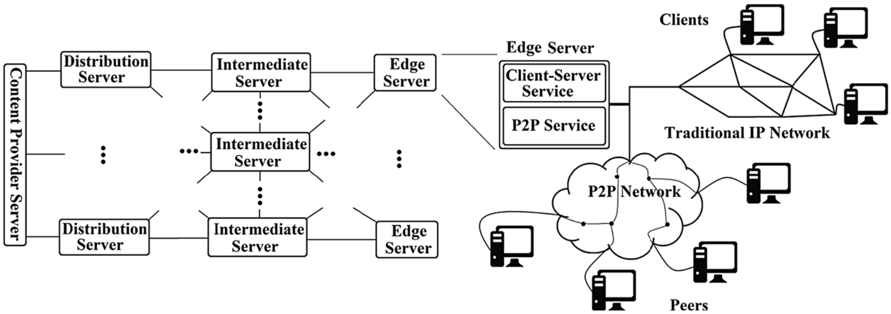

Fig. 2 Architecture of a Hybrid CDN–P2P network

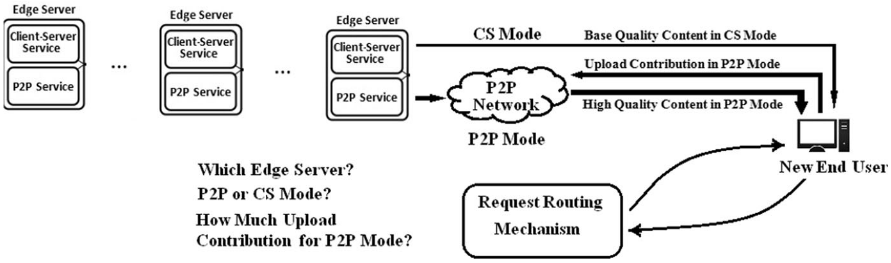

Fig. 3 The RR mechanism in HCDN

HCDNs are expected to keep the network traffic ISP-friendly [13]. In other words, in the content delivery process, HCDNs must not challenge the ISPs with network traffic patterns with divers and far destinations. Therefore, the RR mechanism must keep the assignment of the end-users and edge servers as local as possible. In order to preserve the locality of traffic, we have confined the selected edge server to the edge servers in the vicinity of the end-user, obtained from a traditional DNS-based request routing engine popular in commercial CDNs.

3.2 Economic Model of HCDN

A Hybrid CDN–P2P network contracts SLAs with the content provider to distribute the intended content using Client–Server (CS) and hybrid (P2P) modes. Table 1 summarizes the notations used in this paper to model economics and performance of the HCDN.

The revenue function in the contracted SLA for distribution of content i between the HCDN provider and the content provider is assumed to be as follows:

$$R_{SLAi} = P_{P2P,i} \cdot BW_{P2P,i} \cdot N_{totalP2P,i} + P_{CS,i} \cdot BW_{CS,i} \cdot N_{totalCS,i}, \quad (1)$$

where R_{SLAi} determines the revenue of the Hybrid CDN provider based on the SLA_i. $N_{totalCS,i}$ and $N_{totalP2P,i}$ represent the total number of users served with content i using CS and P2P approaches, respectively. $P_{CS,i}$ and $P_{P2P,i}$ denote the contracted

Table 1 Summary of notations

Notation	Description
R_{SLAi}	Revenue of the Hybrid CDN provider based on SLA_i
$N_{totalCS,i}$	Total number of users served with content i using CS approach
$N_{totalP2P,i}$	Total number of users served with content i using P2P approach
$P_{CS,i}$	Price of bandwidth in CS mode for content i
$P_{P2P,i}$	Price of bandwidth in P2P mode for content i
P_ratio	Pricing ratio ($P_{P2P,i}/P_{CS,i}$)
$BW_{CS,i}$	Bandwidth of content i in CS mode
$BW_{P2P,i}$	Bandwidth of content i in P2P mode
B_ratio	Ratio of P2P stream bandwidth to CS stream bandwidth ($BW_{P2P,i,i}/BW\text{-}_{CS,i}$)
$BW_{ES,i}$	Total bandwidth consumption for distribution of content i at the edge server ES
$BW_{CS,ES,i}$	Bandwidth spent for distribution of the content i in CS mode at the edge server ES
$BW_{P2P,ES,i}$	Bandwidth spent for distribution of the content i in P2P mode at the edge server ES
$N_{CS,ES,i}$	Number of end-users receiving content i in CS mode from edge server ES
$N_{P2P,ES,i}$	Number of end-users receiving content i in P2P mode from edge server ES
$\alpha_{ES,i}$	Inefficiency factor of distribution of content i in P2P mode at edge server ES
BWP_{ES}	Price of bandwidth at edge serve ES
$Cost_{ES,i}$	Cost of distribution of content i at edge server ES
$Replicas_i$	Set of edge servers containing replicas of the content i
$RPCost_{SLAi}$	Costs spent by RP mechanism for replication of content i
U_{SLAi}	Profit or utility of the Hybrid CDN–P2P network due to SLA_i
U_{User}	Utility of the $User$ due to receiving the content i in either CS or P2P modes
$P_{User,D}$	Price of the $User$'s download bandwidth
$P_{User,U}$	Price of the $User$'s upload bandwidth
β_{User}	Ratio of the $User$'s upload to download bandwidth in P2P mode
$P2P\text{-}_{ES,i}$	Set of all P2P end-users receiving their service from ES
$CS_{ES,i}$	Set of all CS end-users receiving their service from ES
DLC_{User}	Capacity of $User$'s downlink
ULC_{User}	Capacity of $User$'s uplink
$Max\_Contribution_{User}$	Maximum contribution of the $User$ in P2P mode
$PRF(BW)$	Preference function of $User$
$TRR(i, User)$	Set of local edge servers containing replicas of content i introduced by the traditional request routing mechanism
$OptES_{User}$	Selected optimum ES to serve $User$

prices of bandwidth in CS and P2P modes. The bandwidth of content i in CS and P2P modes is indicated by $BW_{CS,i}$ and $BW_{P2P,i}$, respectively. In order to incentivize the HCDN to offer P2P service and also prevent it from becoming a pure CDN, it is assumed that

$$BW_{CS,i} \cdot P_{CS,i} > BW_{P2P,i} \cdot P_{P2P,i} > 0. \tag{2}$$

Additionally,

$$BW_{CS,i} << BW_{P2P,i}, \tag{3}$$

guaranties that users have incentives to contribute to the P2P content delivery. The amount of bandwidth an edge server spends to serve end-users interested in receiving the content i, depends on the number of end-users served with each of the CS and P2P modes and is expressed as follows:

$$BW_{ES,i} = BW_{CS,ES,i} + BW_{P2P,ES,i} = BW_{CS,i} \cdot N_{CS,ES,i} + \alpha_{ES,i} \cdot BW_{P2P,i} \cdot N_{P2P,ES,i}, \tag{4}$$

where $BW_{ES,i}$, $BW_{CS,ES,i}$ and $BW_{P2P,ES,i}$ symbolize total bandwidth consumption, bandwidth spent for $N_{CS,ES,i}$ CS end-users and bandwidth spent to serve $N_{P2P,ES,i}$ P2P end-users, respectively. $\alpha_{ES,i}$ represents the inefficiency factor of the P2P content delivery for content i at this edge server. This variable belongs to [0,1] and reflects the fraction of the bandwidth spent by the edge server to the total bandwidth delivered to it. It is obvious that from the HCDN's point of view less value of this variable is desired.

Prices of bandwidth at different edge servers (in practice) are variable and represented by $BWPrice_{ES}$. So the expenditures or cost function of an edge server is quantified using (Eq. 5) and denoted by $Cost_{ES,i}$.

$$Cost_{ES,i} = BW_{ES,i} \cdot BWPrice_{ES} \tag{5}$$

The cost function of the content distribution at the edge servers in the Hybrid CDN–P2P network for SLA_i can be represented as:

$$Cost_{SLAi} = \sum_{\mathrm{ES} \in Replicas_i} Cost_{ES,i} + RPCost_{SLAi}, \tag{6}$$

where the set $Replicas_i$ denotes all the edge servers containing a replica of the content i and $RPCost_{SLAi}$ indicates the costs spent by the RP mechanism for replication of this content. As we are about to design an RR mechanism, $Replicas_i$ and $RPCost_{SLAi}$ are considered constant in this work. Profit or utility of the Hybrid CDN–P2P network is symbolized by U_{SLAi} and can be obtained by

$$U_{SLAi} = R_{SLAi} - Cost_{SLAi} \tag{7}$$

3.3 Economic Model of the End-User's Behavior

End-users are assumed to be rational agents trying to maximize their own utility with preference on high quality content. The resource allocation mechanism does not have any direct way to find the private valuation or the utility function of the end-users. Therefore, the resource allocation mechanism must develop a coherent policy to force the end-user to reveal this private value truthfully. Just for simulation purposes, it is assumed that the preference of end-users is a function of the quality of the received content and directly depends on the bit-rate of the content they receive, denoted by $PRF(BW)$. Equations 8 and 9 give private utility functions of the user *User* for receiving the content i in CS and P2P modes. These private functions hypothetically explain how users decide to choose a traditional low quality CS service or join the P2P network and make a contribution providing the requested upload bandwidth.

$$U_{User,CS,i} = PRF_{User}(BW_{CS,i}) - P_{User,D} \cdot BW_{CS,i} \tag{8}$$

$$U_{User,P2P,i} = PRF_{User}\left(BW_{P2P,i}\right) - P_{User,D} \cdot BW_{P2P,i} - \beta_{User} \cdot P_{User,U} \cdot BW_{P2P,i} \tag{9}$$

U_{User} denotes the expected utility of a user due to receiving the content i in CS or P2P modes. $P_{User,D}$ and $P_{User,U}$ are private functions for pricing the download and upload capacity of the user's link and β_{User} is the ratio of the upload to download bandwidth that the user has to contribute to receive the high quality P2P content from *ES*.

In theory, for the end-user *i,* the maximum desired bandwidth contribution can be calculated using Eq. (10) and is denoted by $Thr\_Max\_Cntrb_{User,i}$.

$$Thr\_Max\_Cntrb_{User,i} = \frac{PRF_{User}(BW_{P2P,i}) - PRF_{User}(BW_{CS,i}) + P_{User,D} \cdot BW_{CS,i} - P_{User,D} \cdot BW_{P2P,i}}{P_{User,U}} \tag{10}$$

Considering the capacity of the uplink and downlink of the user's machine denoted by DLC_{User} and ULC_{User}, the maximum possible upload contribution for the user i is denoted by $Prac\_Max\_Cntrb_{User,i}$ and is calculated by Eq. (11).

$$Prac\_Max\_Cntrb_{User,i} = \begin{cases} 0 & \text{(If the User's machine is not equipped with P2P content delivery software or } \mathrm{DLC_{User}} < \mathrm{BW_{P2P,i}}) \\ Max(0, Min(Thr\_Max\_Cntrb_{User,i}, ULC_{User})) & \text{(Otherwise)} \end{cases} \tag{11}$$

If an end-user finds the bandwidth of the P2P content less than its downlink capacity it is economically beneficial and technically possible to contribute as much as $Prac\_Max\_Cntrb_{User,i}$ to receive the content in the P2P mode; otherwise, the strictly dominating strategy of the user is to receive the CS content and not to contribute to the content delivery process. $Prac\_Max\_Cntrb_{User,i}$ is a private value of the user and the HCDN has no trivial way to find it.

Equation (12) describes the relation between α-$_{ES,i}$ and β_{User}.

$$\alpha_{ES,i} = 1 - \frac{\sum_{User \in P2P_{ES},i} \beta_{User}}{|P2P_{ES,i}|} \tag{12}$$

Here, $P2P_{ES,i}$ is set of all P2P end-users receiving their service from ES. Obviously we have

$$\forall(ES, i) : 0 \leq \alpha_{ES,i} \leq 1 \tag{13}$$

Note that β_{User} is determined by the RR mechanism. Considering the fact that in truthful auctions the result (accept or reject and the equilibrium price) do not have any relation with the bided price, we have,

$$\beta_{User} \cdot BW_{P2P,i} \leq Prac\_Max\_Cntrb_{User,i}. \tag{14}$$

3.4 Formal Model of the Problem

In order to introduce the resource allocation mechanism formally, we employ the notation used in economic mechanism design theory, illustrated in Fig. 4 [33]. In this domain the problem is introduced by specifying two parameters Θ and F, environment space and goal function [33]. The environment space of the problem is a set of all instances of the problem. An instance of the problem or $\theta \in \Theta$ consists of the current state of the system and the parameters of users. As the outcome of the problem is the maximum profit, outcome space, Z, is a single dimension and is a subset of R^+. In this notation, F describes the goal function of the mechanism, F: $\Theta \rightarrow Z$.

An economic mechanism is denoted by $\pi = (M, \mu, h)$ and consists of three elements, a message space, symbolized by M, an equilibrium message correspondence, denoted by μ, and an outcome function, denoted by h [33], where μ: $\Theta \rightarrow M$, and h: $M \rightarrow Z$. The message space M consists of the messages available for communication. The group equilibrium message correspondence μ associates with each environment, θ, the set of messages, $\mu(\theta)$, that are equilibrium or stationary messages for all the agents. The outcome function h translates messages into outcomes. Thus, the mechanism $\pi = (M, \mu, h)$, when operated in an environment θ leads to the outcome $h(\mu(\theta))$ in Z. If it is the case for all environments, θ, in the given space, Θ, the mechanism π leads to a desirable outcome in that environment, we say that π realizes F on Θ.

In this paper, an instance of the problem θ is described as follows:

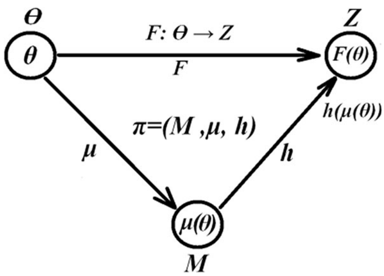

Fig. 4 Notations used to introduce an economic mechanism

- SLA_i for distribution of content *i*.
- A set of local HCDN edge servers containing replicas of requested content introduced by a traditional request routing mechanism, *TRR*(*i,End_User*), and their current state including: BWP_{ES}, $BW_{CS,ES,i}$, $BW_{P2P,ES,i}$, $N_{CS,ES}$, $N_{P2P,ES}$, and $\alpha_{ES,i}$.

Objective function, *F*, is defined to maximize the net profit of the HCDN provider due to serving the end-user *User* from the edge server *ES* and is quantified as follows:

$$F(\theta) = \begin{cases} (P_{CS,i} - BWP_{ES}) \cdot BW_{CS,i} & \text{(CS mode)} \\ P_{P2P,i} \cdot BW_{P2P,i} - (1 - \beta_{User}) \cdot BW_{P2P,i} \cdot BWP_{ES} & \text{(P2P mode)} \end{cases} \tag{15}$$

ES represents the selected edge server from the set of edge servers in the vicinity of the User and containing a replica of *i* denoted by *TRR*(*i,End_User*) obtained from a traditional DNS-based request routing system. In the CS mode, the only optimization variable is the address of the selected edge server, *ES*. In the P2P mode, $(1 - \beta_{User}) \cdot BW_{\mathrm{P2P}}$ reflects the amount of bandwidth that the HCDN spends to serve the end-user in the P2P mode. Therefore, in order to maximize the net profit of the HCDN due to serving an end-user in the P2P mode, it is needed to select the optimum edge server (*ES*) and tune the amount of the end-user's contribution by optimizing β_{User}. Therefore, in order to maximize $F(\theta)$, the mechanism must tune two variables, β_{User} and *ES*.

4 Mechanism Design

For every user, the resource allocation mechanism is required to answer two key questions. First, if the user is interested in receiving the content in the P2P mode, how much must it pay (contribute) in the form of an upload bandwidth to join the P2P service? Second, among near servers containing replicas of the requested content, which server must take the responsibility to serve the user? In order to design the mechanism, first, it is needed to study features of the problem from an economics point of view.

4.1 Features of the Problem

In this domain, we have assumed that like most of the commercial CDNs, the HCDN has the sole responsibility for distribution of the content. Therefore, in this domain the HCDN is able to leverage its monopoly power to determine the optimum upload bandwidth contribution of the end-user and select the best server. Based on microeconomics theory of monopolistic markets, a monopoly is a price maker [37], and therefore, the optimum outcome of the problem can be theoretically calculated by finding the optimum monopoly solution [38]. The revenue and cost function of the Hybrid CDN–P2P network, (Eq. 1) and (Eq. 6), directly depend on the private utility function of users, (Eq. 8), which is not disclosed. Therefore, solving the problem using a straight-forward monopoly approach is not trivial.

It is obvious that due to the selfish behavior of the end-users, those interested in high quality content, do not prefer to reveal their maximum upload contribution. If the resource allocation mechanism finds it economically beneficial to serve the user in the P2P mode, the best strategy is to charge the user the highest possible upload bandwidth. In other words, the maximum possible value of β_{User} maximizes the objective function. This strategy does not depend on the selected server. In order to determine β_{User}, we employ Random Sampling Profit Extract (RSPE) envy-free profit maximizing truthful auction [28]. RSPE as an economic mechanism has the following features;

- *Truthful*
  Hartline and McGrew [39] proved that RSPE is truthful. In a truthful auction, revealing one's true valuation (the maximum bandwidth contribution) as one's bid is an optimal strategy for each bidder regardless of the bids of the other bidders [39]. This feature prevents the end-users from hiding their private values and makes it practical to rely on the amount of bandwidth contribution declared by them to optimize the resource allocation, maximize the contribution of end-users, and prevent free-riding.
- *Envy-free*
  RSPE belongs to the class of envy-free auctions [34]. An envy-free mechanism guarantees the fairness criterion. It ensures that every customer is maximally satisfied with her allocation given the pricing-scheme. An envy-free solution may be viewed as a stable or "equilibrium" outcome for the customers, in that no customer has an incentive to dispute the allocation. In the economics' literature, the notion of envy-freeness has been used to model fair equilibrium pricing in various settings. This feature ensures that the outcome of the resource allocation mechanism is fair and the variance of the bandwidth contribution of the end-users is small.
- *Profit maximizing*
  RSPE is classified as one of the profit maximizing auctions [28]. Goldberg et al. [34] proved that the competitive ratio of RSPE is 4.

Definition RSPE works as follows [28]:

1. Randomly partition the bids b into two by flipping a fair coin for each bidder and assigning her to b' or b''.
2. Using an optimal single price omniscient auction to compute $R' = F(b')$ and $R'' = F(b'')$, the optimal profits for each part.
3. Run $ProfitExtract_{R'}$ on b'' and $ProfitExtract_{R''}$ on b'.

Definition Optimal single price omniscient auction is defined as follows:

$$F(b) = Max_{1 \leq i \leq n}(i \cdot b_i). \tag{16}$$

Definition The digital goods auction profit extractor with the target profit R ($ProfitExtract_R$) sells to the largest group of k bidders that can equally share R and charges these k bidders R/k and rejects all others.

While the RSPE approach determines the optimum amount of bandwidth contribution for the end-users (price), we need another economic mechanism to assign an end-user to the most profitable edge server and determine the production quantity. Considering the monopolistic feature of the problem, it is practical to distribute the monopolistic power of the HCDN among the edge servers and apply an oligopolistic market to determine the most profitable server among the edge servers neighboring the end-user. Oligopolistic markets are based on collusion and are able to increase their benefit to the maximum, keeping the prices as much as the monopoly price [37]. The foundation of these markets is based on the cooperation of a small group of sellers splitting the market and acting as price setters. It is proved that the equilibrium for an oligopoly is the Nash equilibrium[4] [37]. As mentioned earlier, the price of P2P service, $\beta_{User} \, . \, BW_{P2P,i,}$ is determined by (Eq. 11), and the competition of producers, edge servers, would be only on the quantity of production. In this domain, due to the small number of neighboring edge servers, the implementation of oligopoly is trivial. Based on (Eq. 16), the optimum Edge Server denoted by $OptES_{User}$ can be selected easily among the candidate edge servers.

$$OptES_{User} = \underset{ES}{\operatorname{argmax}} \; (F(\theta)) : \{ES | ES \in TRR(i, User)\} \tag{17}$$

where ES is the optimization variable and belongs to the set of edge servers.

4.2 Resource Allocation Mechanism

In this section, the Hybrid Resource Allocation mechanism (HRA) is introduced formally as an economic mechanism. The set of messages, M, employed in the HRA mechanism and their abbreviated names are introduced in Table 2. Figure 5 illustrates the flow of $\mu(\theta)$, in the HRA. In the first step, the HRA receives the request of the user in the form of a HCDRQ message. These messages, in addition to the ID of the content and the IP address of the user, contain their maximum desired contribution level to receive the content in the P2P mode. Users are assumed to be rational and aware that a truthful profit maximizing auction is employed. Thus, the dominant strategy for the user is to declare its maximum possible upload contribution level truthfully [28] quantified by (Eq. 11). Pseudo-code 1 in "Appendix" describes the HRA process in an end-user's machine. In order to implement the HRA mechanism, a Hybrid Resource Allocation Server (HRAS) is employed. Pseudo-code 2 in "Appendix" describes the HRA process in the HRAS. The third part of the HRA message passing mechanism is implemented in the edge servers. Pseudo-code 3 in "Appendix" explains the HRA process in an edge server.

Figure 5 illustrates the message passing sequence in HRA. The HRAS gathers the Hybrid Content Distribution Request (HCDRQ) messages during a period of ΔT.

[4] Nash equilibrium: a situation in which economic actors interacting with one another, each choose their best strategy given the strategies that all the other actors have chosen.

Table 2 Message space (M) employed to implement the HRA mechanism

Message name	Source	Destination	Content	Comments
Hybrid Content Distribution Request (HCDRQ)	End-user	(Hybrid RA Server) HRAS	(Object ID, Address of User, Desired Upload Contribution)	The employed auction, RSPE, is truthful so the user is forced to reveal its truthful maximum value of Desired Upload Contribution
Expected Net-Profit Request (ENPRQ)	RRHS	Edge servers	(Object ID, Address of User, Determined Upload Contribution)	HRAS splits the set of end-users requesting to receive the content in ΔT to two partitions. Then calculates Determined Upload Contribution using Desired Upload Contribution announced by them truthfully relying on RSPE. Then requests the neighboring edge servers (introduced by TRR) to announce their expected net profit due to serving the end-users
Expected Net-Profit Response (ENPRS)	Edge servers	HRAS	(Expected Net-Profit, Mode)	Each edge server applies (Eq. 7) to calculate its expected net profit due to serving the user with determined upload contribution either in P2P or CS modes
Hybrid Content Distribution Response (HCDRS)	HRAS	End-user	(Address of Edge Server, Mode, Determined Upload Contribution)	HRAS selects the address of the Edge server with the maximum expected net-profit and replies the End-user with the address, mode and determined upload contribution

At the end of ΔT, the HRAS uses the RSPE procedure to calculate the optimum upload bandwidth contribution of the end-users. In this way, the HRAS randomly splits the new set of end-users into two partitions. Then it calculates the optimum price (upload contribution) for each partition using Eq. (16). After that, for each request it determines that if the request is accepted in the P2P content delivery auction or not. In other words all the bids with desired upload bandwidth less than the determined upload contribution will be rejected. Through this procedure, all the clients having bids (desired upload contribution) more than the optimal price are accepted in the P2P content delivery and must contribute the same amount of upload bandwidth determined by using the RSPE approach. Others are rejected and served in the CS mode. It is obvious that for CS end-users, the optimum of β_{User} will be zero. Having the optimum value of $\beta_{User\text{-}}$, the HRAS determines the neighboring edge servers for each end-user through a traditional DNS-based RR mechanism. Steps 2 and 3 (oligopolistic market) are only performed for end-users winning the RSPE auction and joining P2P networks.

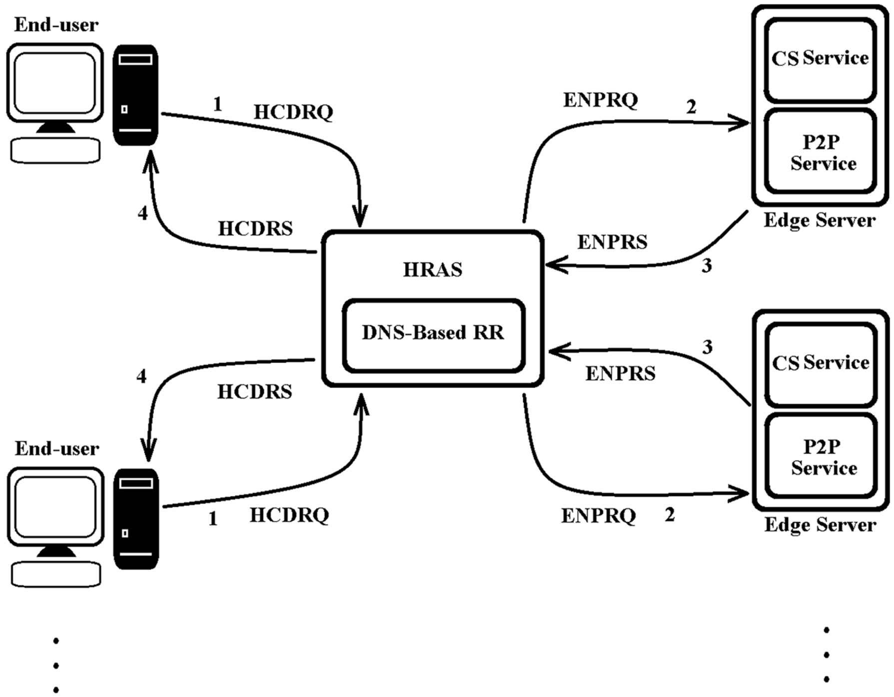

Fig. 5 Request routing mechanism of Hybrid CDN–P2P network (HRA mechanism)

At the step 2, the neighboring edge servers are requested to announce their expected net profit with the suggested upload contribution through an Expected Net-Profit Request (ENPRQ) message.

In step 3, the HRAS receives the Expected Net-Profit Response (ENPRS) messages and selects the edge server with the maximum expected net profit to serve the user the in hybrid mode. At the step 4 the end-user receives the preferred edge server's address, content delivery mode, and (if required) the requested upload contribution through an HCDRS message. For rejected requests, (end-users with a desired contribution less than the determined contribution level and loosing the RSPE auction) the content delivery mode would be a CS mode. Once the HRA decided to accept an end-user in the P2P content delivery process, the end-user does not have any incentives to change the content delivery mode. In addition, the HCDN does not prefer the CS mode, because based on its utility function, it gains more net-profit in the P2P mode.

From an economic mechanism design theory point of view, it can be said that the HRA relies on the RSPE profit maximizing auction, (Eq. 16) that has proved to be able to maximize the revenue of the digital goods auction, (β_{User} in this work). In addition, the HRA is able to select the most profitable edge server and content delivery mode using the oligopolistic market. The oligopolistic market is solved using (Eq. 17). Therefore, it can be concluded that the result of the HRA's message passing process introduced in Fig. 5, $h(\mu(\theta))$ equals the objective function, (Eq. 15). In other words, the HRA realizes the objective function $F(\theta)$ and $h(\mu(\theta)) = F(\theta)$.

The HRAS has a close relationship with DNS-based Request Routing (RR) mechanism and it also regularly forwards requests of the users to find near replicas. So the best possible place for the HRAS servers seems to be on the same physical machine or network of presence of the DNS-based traditional RR. If the HRA finds all the servers listed in the DNS-based RR response message saturated, it queries a higher level DNS-based RR for potential servers. This case happens only when all the local edge servers are saturated, thus, it harms the locality of traffic but improves the reliability of the system and increases the potential of the system to overcome flash-crowds.

In "Appendix", Pseudo-codes 1, 2, and 3 present the HRA mechanism in an end-user's machine, in an HRAS server and inside an edge server.

5 Performance Evaluation

5.1 Experimental Setup

A custom-written simulation test-bed was employed to study the performance of the HRA. The discrete event simulation was written in C++, compiled using a Borland C++ 5.02 compiler and was run on a Windows machine with two 3.2 GHz processing cores and 4 GB of RAM. Since the resource allocation mechanism in the HRA demands strategic decision of users, and it is not possible to have thousands of real users simultaneously, their behavior was also simulated and fed to the test-bed. Although the HRA mechanism is theoretically able to solve the problem in any environment, maximum effort was made to set the parameters as real as possible. Some of the parameters of the environment (e.g., sequence and source address of requests, location of edge servers and replicas) were set using real log files of a traditional CDN during the month of May 2013 and operating in Australia. Other parameters were assigned based on the approximate distribution of parameters in the geographical domain of the referenced CDN.

Among the parameters of end-users, the source IP address and the sequence of requests were extracted from the CDN trace log files. Since measurement of different features of users is not in the domain of this research, some simplifying assumptions were made to set their parameters. Values of upload and download capacities and their respective prices were assumed as random variables with normal distribution. Based on practical observations, the standard deviation of the random variable was assumed to be 1/4 of its mean. The values of the preferences of the users were also set using the same approach.

A typical 1000-s streaming content with a bandwidth of 500 Kbps was considered as the CS service. The ΔT was set to be 10 s. The bandwidth of the P2P content was assumed as double that of the CS service (1 Mbps). The price of the bandwidth for the CS service was extracted from the SLA of the CDN and in order to keep the SLA incentive compatible, the price of the bandwidth for the P2P service was assumed as 1/4 of the CS bandwidth price. Considering (Eq. 1) the cost of the P2P service per user in the SLA for the content provider was half of the CS service. It is assumed that there were 1000 edge servers in the system and HRP [36]

Table 3 Summary of parameters used in experiments

Parameter	Value	Comments
ΔT	10 s	The period of time that HRA waits to gather enough requests
$BW_{CS,i}$	0.5 Mbps	Bit-rate of an average quality video
$BW_{P2P,i}$	1 Mbps	Bit-rate of a good quality video
$P_{CS,i}$	80 $/Gbps	Price of traditional CDN service in the SLA
$P_{P2P,i}$	20 $/Gbps	To keep the SLA incentive compatible, the price of CS service is assumed to be two times of the P2P service price per user
$BWPrice_{Edge\_Server}$	[60, 76] $/Gbps	Network bandwidth price at different edge servers
$Price_{User,D}$	100 $/Gbps	Average price of download bandwidth, A normal distribution with standard deviation of 1/4 average is used in the simulation
$Price_{User,U}$	200 $/Gbps	Average price of upload bandwidth, A normal distribution with standard deviation of 1/4 average is used in the simulation
DLC_{User}	4 Mbps	Average of download bandwidth in geographical domain of the referenced CDN
ULC_{User}	1 Mbps	Average of upload bandwidth in geographical domain of the referenced CDN

was applied as the replica placement strategy. Table 3 represents the values of the parameters used in these experiments.

In our experiments, a traditional DNS-based RR returned the address of the 3 nearest servers for each request and the HRAS gradually assigned the end-users with corresponding edge servers. In order to keep the experiments comparable, the churn rate of the end-users was not considered. In other words, the users entered the system in an accumulative manner to enable us to study the behavior of the HRA increasing the load without worrying about leaving peers due to the churning. When the simulation started, the users requested for the content, received the HCDRS message, and made a strategic decision on, joining the P2P network or receiving the CS content.

5.2 Experiments

In order to study the performance of an HRA, we examined its outcome in 3 different ways. We studied the performance of HRA under a normal workload in the first experiment. The second experiment was devoted to the economic comparison of an HRA mechanism in a typical HCDN business against a traditional CDN economy. The third experiment compares the performance of HRA mechanism with other resource scheduling strategies.

5.2.1 Performance

In the first experiment an HRA was employed as the resource allocation and request routing mechanism of a typical HCDN business. The experiment studied the performance of the system distributing a 1000-s streaming video and serving a total number of 1 million requests.

Figure 6 illustrates the number of requests submitted to the HCDN in both the CS and hybrid modes (denoted by *ReqCS* and *ReqP2P*). This figure also represents the number of CS and P2P end-users receiving service from the HCDN (denoted by *NCS* and *NP2P*) when the HRA approach was applied. As it can be obviously seen, when the number of requests increased, the number of end-users served in the P2P mode increased and got closer to the number of requests for the content in the hybrid mode. In other words, when the number of requests went above the bootstrapping threshold, the system succeeded to serve the majority of hybrid requests in the P2P mode. Here, the bootstrapping threshold was defined as the minimum number of P2P end-users that decreased the inefficiency factor of the P2P content delivery at an edge server below 1. This threshold was calculated by each edge server separately and depended on many factors including the popularity of the P2P content and the prices of the resources in the server.

Figure 7 represents the Total Bandwidth Delivered to the Users (TBDU), the Total Bandwidth Spent by Edge-server of HCDN (TBSE), and the Total Bandwidth Contribution of the Users (TBCU). As it can be seen, when the number of requests went beyond the bootstrapping threshold, P2P content delivery began and total bandwidth contribution of the end-users became increasingly significant. When the number of requests was large, for example when the system was serving 1 million simultaneous requests, the end-users supplied a big fraction of the delivered bandwidth. The increasing trend of the total bandwidth consumption of the HCDN with an increasing number of requests (TBSE), vividly shows that when the number of requests is small, behavior of the HCDN is similar to a traditional CDN. In other words, the HCDN affords all the delivered bandwidth and the TBSE increased linearly with respect to the number of concurrent requests. However, when the number of simultaneous requests increased above the bootstrapping threshold, the

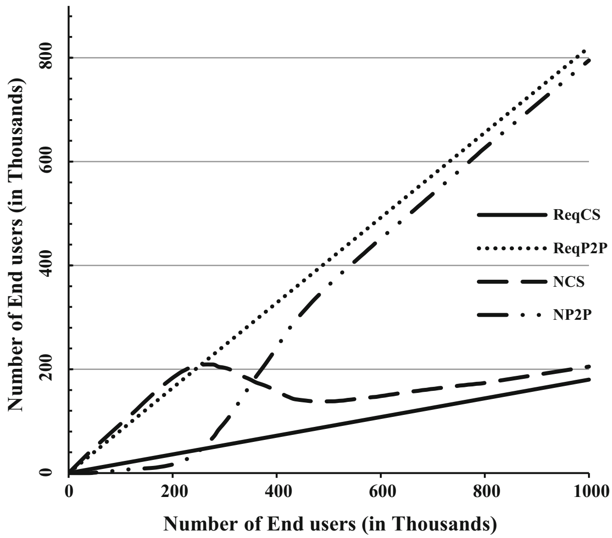

Fig. 6 Number of requests and end-users served in CS and P2P modes

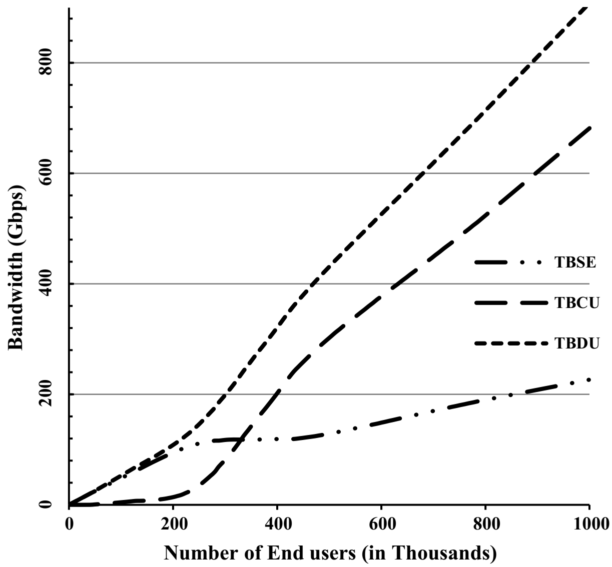

Fig. 7 Performance metrics of HCDN. Total Bandwidth spent by edge servers (TBSE), Total Bandwidth Contribution of Users (TBCU) and Total Bandwidth Delivered to Users (TBDU)

HCDN benefitted from contribution of the end-users and its bandwidth consumption increased sub-linearly, which implies that the HCDN is more scalable compared to traditional CDN architecture.

Figure 8 reveals the economics of content distribution in the HCDN environment using an HRA. As it can be seen, the economics of the system was affected by the bandwidth allocation (Fig. 7). When the number of requests was below the bootstrapping threshold, the economic behavior of the system was like a traditional

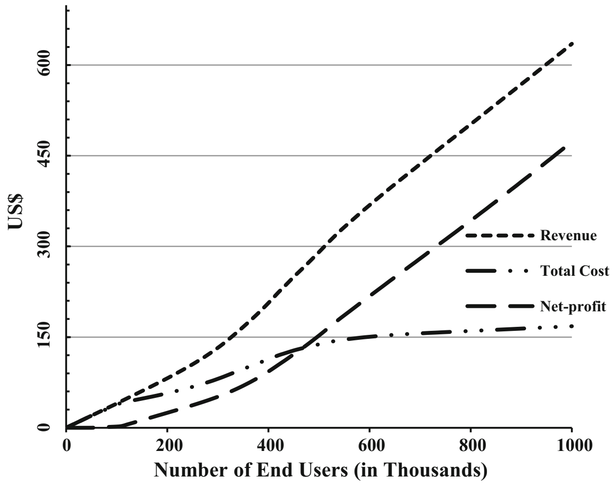

Fig. 8 Economics of content delivery by HCDN

CDN. In other words, the revenue, cost and net profit of the system increased linearly with the increase of the population of the end-users. Around the bootstrapping threshold, the economics of the system, like its bandwidth consumption behavior, had a nonlinear trend. Finally, when the number of requests became significant, the cost of the system increased slowly and sub-linearly; therefore, the net profit of the content delivery improved with more slope than its revenue.

Figure 9 reports a variation of the economic efficiency of the P2P content delivery ($1-\alpha$) with an increase in the population of the end-users. Considering the graph, it can be observed that when the HCDN received enough requests to bootstrap the P2P content delivery, it needed to afford a big fraction of the traffic injected into the P2P networks. As it also can be observed, when the number of requests grew enough, more edge servers passed the bootstrapping threshold and the fraction of traffic that the HCDN spent on the P2P content delivery became significantly small, i.e., for 1 million end-users, only 14 % of the P2P traffic sources from the edge servers directly.

Table 4 reports the key performance and economic metrics of the system under low, medium, and high load (200,000, 400,000, and 1 million simultaneous users). As it can be seen, when the total number of requests was small, a few end-users succeeded to receive the content in the P2P mode. Additionally, the HCDN could not benefit from the contribution of these end-users and α (0.918) remained close to 1, which means that almost all of the bandwidth delivered in the P2P mode was supplied by the HCDN. When the total number of requests was 400,000, the HCDN started to serve hybrid requests in the P2P mode. In this situation, still some of the edge servers did not pass the bootstrapping threshold. Therefore, among the end-users 26 % ($100 \times (328{,}000 - 241{,}736)/328{,}000$) of them did not succeed to receive the high quality P2P content. In this situation, 74 % of end-users benefitted from the high quality content and improvement of α (from 0.918 to 0.307), which represents that even with a medium frequency of requests, the HRA has succeeded to benefit from the bandwidth

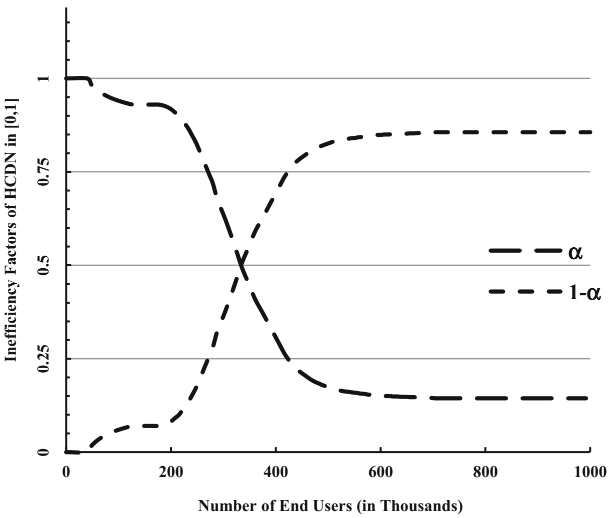

Fig. 9 Efficiency metrics of hybrid content delivery

Table 4 Key performance metrics of HCDN applying HRA

	Total number of requests	Requests in CS mode	Requests in hybrid mode	Number of end-users served in CS mode	Number of end-users served in P2P mode	Total bandwidth delivered (Gbps)	Total bandwidth contributed by P2P end-users (Gbps)	Bandwidth spent By the HCDN (Gbps)	Total cost ($)	Revenue ($)	Net-profit ($)	α
Light load	200,000	36,000	164,000	183,436	16,564	108.28	13.83	94.45	57.11	81.87	24.75	0.918
Medium load	400,000	72,000	328,000	158,264	241,736	320.87	201.85	119.02	113.39	206.44	93.06	0.307
High load	1,000,000	180,000	820,000	205,080	794,920	908.20	681.69	226.51	167.96	635.18	473.46	0.144

contribution of the end-users. The last row of the table shows that when the HCDN received a high load of requests (1 million), the majority of hybrid end-users (79.4 %) succeeded to receive the high quality content in the P2P mode. The HCDN supplied only 24.8 % (226/908) of the total network traffic delivered to the end-users. In the P2P mode, only 14.4 % of the traffic was sourced from the edge servers, ($\alpha = 0.144$). In other words, it had succeeded to serve most of the end-users interested in double quality content in the P2P mode. Moreover, it prevented them from free-riding. The small value of α (the fraction of bandwidth spent by the HCDN for the P2P content delivery) proved that the HRA mechanism succeeded to encourage the hybrid end-users to contribute their upload bandwidth to the P2P content delivery.

5.2.2 Economics

Figure 10 compares economics of content distribution relying on the HRA and using the HCDN architecture with a pure CDN. This experiment revealed several microeconomic facts. First, although relying on the hybrid content delivery, a big majority of the end-users received the content with double quality, but the content provider had to pay (revenue of HCDN) much less than twice of the expenses of a pure CDN architecture (revenue of CDN). Second, the costs spent by the HCDN provider to deliver the content to the end-users, especially when the load was considerably high, was considerably small, even less than the cost for content delivery in a pure CDN architecture with half the quality. Third, the HCDN earned several times more net-profit compared to the traditional CDN. To sum it up, all three sides of the content delivery market benefitted from the HCDN architecture, the HCDN provider had more net-profit, the content provider paid less for high quality content and the majority of the end-users enjoyed higher the quality content.

In order to study the economics of the HCDN architecture with an HRA resource allocation mechanism, a pure CDN business was implemented and fed with the same flow of requests. Figure 8 compares the economic metrics of the HCDN with a traditional CDN. In this graph, the net-profit, cost, and revenue of both systems were reported. The differences in the economics of the content distribution relying on the

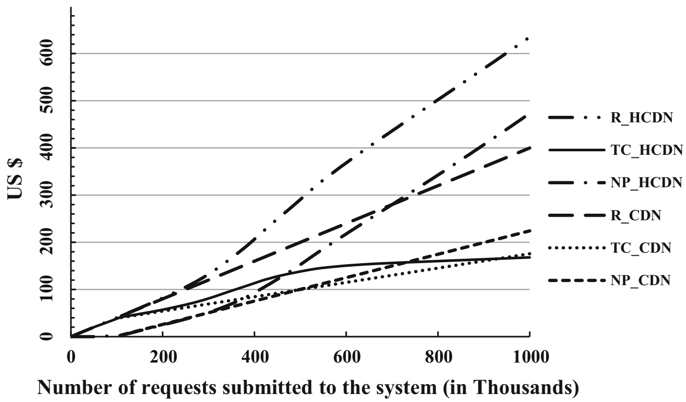

Fig. 10 Comparison of economics of content distribution in HCDN and CDN

HCDN and CDN architectures appeared just after bootstrapping threshold of the P2P content delivery. Comparison of the revenue function for the HCDN and pure CDN content delivery approaches depicts that, although relying on HCDN architecture, the majority of the end-users were served with double quality content, the content provider paid much less than twice the costs paid for pure CDN content delivery. This graph also shows that the net-profit of the HCDN was several times more and has a more increasing trend compared to the net-profit of the CDN. Comparison of the cost function for these architectures reveals that although the HCDN delivered much more traffic to its clients, its total cost of content delivery was comparable to the one of the traditional CDN architecture. Additionally, when the number of concurrent end-users became significantly high, the costs spent by the HCDN became less than costs spent by the CDN architecture.

5.2.3 Comparison of HRA with Other Strategies

In order to study the performance of the HRA, we implemented three other request routing strategies. These strategies include the following:

- Oligopolistic RR with Myerson auction [10] (HRR). Instead of an RSPE auction which does not require any tuning, a Myerson auction is employed. It estimates the statistical distribution of the private values and determines the contribution level of the hybrid end-users.
- Oligopolistic RR with Vickrey auction. Instead of an RSPE auction a Vickrey Auction receives requests and determines the contribution level using a second price auction.
- Pure CDN where the P2P content delivery is shut down and all requests are served in the CS mode.

As shown in Fig. 11, the HRA is able to provide more net profit compared to all other approaches. This observation verifies that Vickrey and all the class of VCG

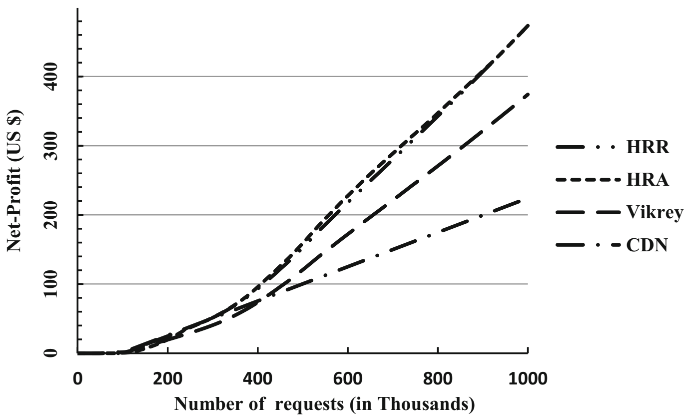

Fig. 11 Comparison of net profit in different mechanisms varying number of end-users

truthful auctions are not able to maximize the net profit and just benefit social welfare of the end-users [28]. In fact, the class of VCG mechanisms are able to reveal private values of the end-users but they are not able to benefit from this information, maximize net profit nor maximize the total payment of the end-users (in the form of upload bandwidth). As expected, the lowest outcome belongs to the pure CS strategy.

As it can be obviously seen, the HRA has approximately the same behavior as the HRR mechanism employed in [10]. In order to compare the performances of HRA and HRR, more specifically Fig. 12, compares the outcomes of these mechanisms under a light to medium load. As it can be seen, compared to the HRR, the HRA begins an efficient P2P content delivery with a less number of requests. In other words, the bootstrapping threshold of the HRA is smaller than that of the HRR. The only reason for this is the fact that the HRR requires achieving estimations for the statistical distribution of the optimum upload contribution of the end-users. Therefore, when the number of observations is small or there is even a small magnitude of noise (outliers) in the observations, (declared truthfully by the end-users), the HCDN earns less net profit by relying on the HRR.

In order to study the fairness of the HRA, the bandwidth contribution of the CS end-users is excluded from the study because the CS end-users contribute no upload bandwidth into the P2P content delivery. Figures 13 and 14 report the average and standard deviation of the upload bandwidth contribution of the P2P end-users in the HCDN using the HRA, HRR and Vickrey request allocation strategies. As it can be seen, the highest average upload bandwidth contribution of the P2P end-users in HCDN belongs to the HRA mechanism. Also, it is visible that as the number of the P2P end-users increases, due to the more accurate estimates of the statistical distributions used in the HRR, its outcome gets closer to the outcome of the HRA. Considering the average upload bandwidth contribution of the P2P end-users in Vickrey mechanism; it can be concluded that by using this mechanism, users contributed their upload capacity into the P2P content distribution less. These observations can justify the trend of variation of the net-profit of various strategies plotted in Fig. 11.

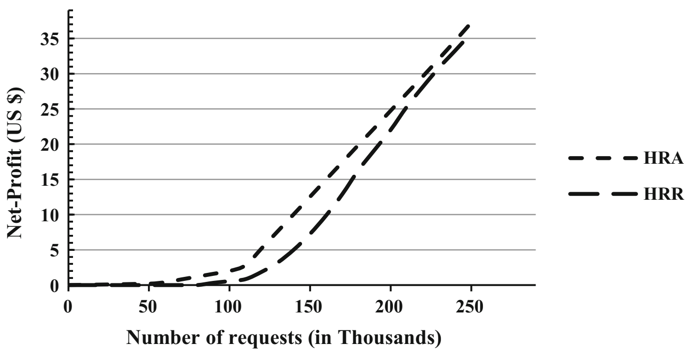

Fig. 12 Net-profit of content distribution in HCDN using HRA and HRR requests allocation strategies under low to medium load

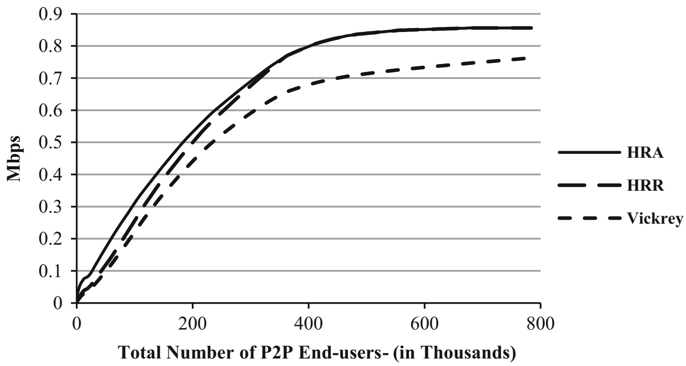

Fig. 13 Average of upload bandwidth contribution of P2P end-users in HCDN using HRA, HRR and Vickrey request allocation strategies

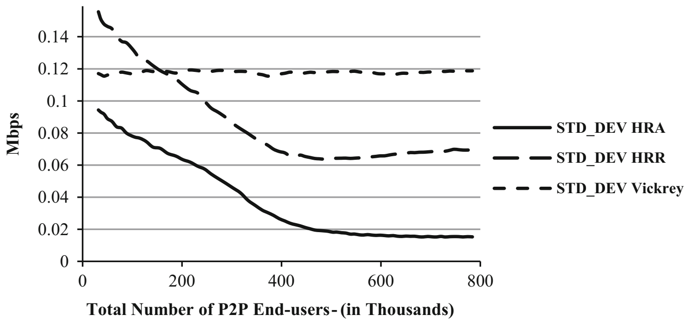

Fig. 14 Standard deviation of upload bandwidth contribution of P2P end-users using HRA, HRR and Vickrey request allocation strategies

Figure 14 represents the standard deviation of an upload bandwidth contribution of peers using the HRA, HRR and Vickrey request allocation strategies. Based on this graph, it can be concluded that, when the number of requests is small, the HRR mechanism has the worst fairness; however, when the number of end-users becomes significant, the standard deviation of bandwidth contribution of peers decreases and fairness improves. As it is expected, the HRA as an envy free mechanism has the smallest standard deviation and it has the best fairness with any number of peers. The standard deviation of the Vickrey mechanism is approximately constant and does not depend on the number of peers.

5.3 Practical Implications

Our experiments depict that by employing an economic resource allocation mechanism and relying on the hybrid content delivery approach, it is possible to benefit all three sides of the content distribution economy. In other words, the HRA mechanism enables the HCDN to provide a big fraction of end-users a with higher quality content. It increases the profit of the HCDN provider and decreases the expenditures of the content provider at the same time.

These experiments also show that the RSPE auction, which does not require any statistical information about the private values of the end-users, (upload capacity and desired level of bandwidth contribution), can compete with the optimal profit maximizing Myerson auction. These mechanisms have pretty similar outcomes but since the HRA (RSPE) does not require estimating the statistical distribution of private values, it has a slightly better performance, especially when the load is light and it is hard to estimate the needed statistical parameters for the HRR (Myerson mechanism) or there are some outliers in the private values. Therefore, from a practical point of view, the HRA has many benefits over the previously studied HRR.

6 Conclusion and Future Work

In this paper, a novel resource allocation and request routing mechanism for streaming content distribution in Hybrid CDN–P2P networks is introduced. In order to design the mechanism, the problem introduced formally and HCDN environment modeled mathematically considering the economics of content distribution and the SLA. Maximization of the net profit of the CDN owner is set as the optimization goal. The optimization problem divided into two isolated optimization processes, namely maximizing the requested bandwidth contribution and the optimizing the assignment of the end-users and edge servers. In order to preserve the fairness among the end-users, the former optimization problem was solved via an envy-free mechanism, while the later problem was solved using an oligopolistic mechanism.

Relying on our simulation studies the performance and economics of content distribution using the proposed mechanism (HRA) were studied. Experimental results revealed that the application of the HRA made it possible to serve a big fraction of the end-users with a higher quality content, improve the net profit of the HCDN provider and decrease the expenditures of the content provider at the same time. In order to evaluate the performance of the HRA, some other strategies including the Vickrey second price auction and the previously studied HRR mechanism were implemented. The Experiments showed that compared to all other strategies, the HRA had the best outcome. These comparisons also demonstrated that the HRA was able to benefit from the upload bandwidth of the end-users. The experiments particularly showed that when compared to other strategies, the HRA kept the standard deviation of the bandwidth contribution of the end-users less, which verifies both higher fairness and envy-freeness of the mechanism.

CDNs are expected to tolerate flash crowds; a promising future works would be studying the effect of flash crowds on the performance and economics of content distribution in hybrid CDN–P2P networks. CDNs optimize their performance relying on two key mechanisms: request routing and replica placement. In the future, we will consider studying the integration of these two mechanisms for streaming content distribution in Hybrid CDN–P2P architecture. Cloud computing infrastructures are increasingly attracting the attention of the research community to mediate the high deploying costs of CDNs. Another extension to this work should consider the integration of cloud based CDNs with P2P networks.

Appendix

Pseudo code 1. Implementation of HRA in an end-user's machine.

```
Variables:
Private: float ULC, DLC, Price_{User,D}, Price_{User,U}, desired_β;
Private: float PRF(float BW);      // The private preference function of the end-user;
HCDRQ request;
HCDRS response;
IP_Address my_address;

Request(content i)  //When end-user requested too receive the content i.
{
  desired_β =Calculate_desired_upload_bandwidth_contribution(content i)   // Zero desired_β means CS mode is selected
   request.object_ID =i; request.Address= my_address;  request.Desired_Upload_Contribution= desired_β;
                                                                                    //Fill the request message (HCDRQ)
  request.send(IP_address_of_HRAS);                                                 //Send the request to HRAS
  response.receive(IP_address_of_HRAS); // receive the HCDRS message in response

                                                                          //Send HCDRQ message and Receive HCDRS
  If ((response.requested_β <= desired_β) and (response.mode==P2P))
    {
     Join(Server_IP_address, requested_β,i);                  //The bid accepted. End-user can join the P2P Sub-network
    }
  Else
   {
    Request_CS_Content_Delivery(Server_IP_address, i);       // The bid rejected. End-user must receive the content in CS
mode
   }
}


Calculate_desired_upload_bandwidth_contribution(int i)
   {
       // if the end-user is ready to spend some upload bandwidth to receive the content in
       //P2P mode this function returns desired_β >0 otherwise it returns 0
     If (DLC< BW_{P2P,i}) return (0);    // This end-user do not have enough downlink capacity to receive P2P content.
     Float  Max_Contribution =(PRF_{User}(BW_{P2P,i})-PRF_{User}(BW_{CS,i})+Price_{User,D}.BW_{CS,i}- Price_{User,D}.BW_{P2P,i})/(Price_{User,U});
     If  (Max_Contribution_{User,i}<0) return (0);
                                 //The preference of this User over high QoS is not much bigger than her preference for base
                                 //quality content or the price of download bandwidth denoted by is extreamly expensive
     Max_Contribution=Min(Max_Contribution, ULC_{User}); //Limit the upload contribution to the capacity of the uplink
     Float desired_β= (Max_Contribution_{User,i}/BW_{P2P,i});
     Return (desired_β);
   }
```

Pseudo code 2. Implementation of HRA process in an HRAS server.

```
Constants:
int n=number of contents;
float ΔT=period of time;

Variables:
 HCDRQ request;
 HCDRS response;
Set HCDRQ Requests[n];                    // An array of sets storing HCDRQ requests during the ΔT period
Set HCDRQ b,b',b";
int i;
float P',P";
Set Server local_servers;                 // A local variable for storing result of DNS request
Set ENPRS TRR_responces;

While (True)
{
 For t=0 to ΔT
 {
request.receive();            // run the receive member function of the variable request and receive a request
Requests[request.object_id].insert(request);
          //based on the id of the requested content insert the request in the set of requests for the specific content.
}

For i=1 to n  //for each set of requests for each instance of content
 {
  b=Requests[i];
  b'= Randomly_half(b);                              //randomly put half of the bids in b'
  b"=b-b';
  P'=F(b');                       //calculate the optimum price for the first partition of bids
  P"=F(b");                       //calculate the optimum price for the second partition of bids
  PROFIT_EXTRACT(b',P");
       //decide on accepting the bids in b' with price P" for accepted bids βUser=P" and for rejected requests set βUser=0;
  PROFIT_EXTRACT(b",P');
       //decide on accepting the bids in b" with price P' for accepted bids βUser=P' and for rejected requests set βUser=0;

  For (each request in b)
   {
     Local_servers=DNS_lookup(request.IP_address);
     For (each ES in local servers)
      {
        Fill and Send an ENPRQ message;    //if the request is rejected βUser=0, if it belongs to b' βUser=P", otherwise βUser=P'
                                           //Object ID=i;
        Receive the response in form of ENPRS messages and insert them in the set TRR_responces;

       }
        Select the ENPRS message with max expected net profit. Put the IP_address and Service mode in S_IP and S_mode;
        Construct a response HCDRS message response containing (S_address, S_mode, βUser)
         Send (response, request.IP_address);
   }
 }
```

Pseudo code 3. Implementation of HRA process in an edge server.

```
Variables:
ENPRQ TRR_request;
ENPRS TRR_response;
While (True)
{
   TRR_request.receive();     //Receive the ENPRQ message and store its parameters in local variables including (i, β_User)
   int i=request.i;    //the requested object's ID;
   Float Utility_CS=(P_CS,i-BWP_ES).BW_CS,i;
   Float Utility_P2P=(P_P2P,i. BW_P2P,i )-(1- TRR_request.β_User ).BWP_ES.BW_P2P,i;
   If (Utility_CS> Utility_P2P)
   { //CS mode
     TRR_response.expected_net_profit= Utility_CS;
     TRR_response.Mode=CS;
   }
   Else
   {//P2P mode
     TRR_response.expected_net_profit = Utility_P2P;
     TRR_response.Mode =P2P;
   }
  TRR_response.Send(IP_Address_of_HRAS);
}
```

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