Incentivizing Efficient Content Placement in a Global Content Oriented Network

Chong Wang and John W. Byers
Department of Computer Science, Boston University
{wangch, byers}@cs.bu.edu

***Abstract*—With the primacy of content driving the design of new network architectures as well as the successful CDN business model, it is instructive to reconsider problems of content placement from the context of ISPs. In particular, we focus on a near-term future where architectural support for content has become more explicit, or where ISPs have become more proactive in incorporating content hosting into their business model, or both. In such a global content oriented network, studying the economic incentives for ISPs to focus on content placement and hosting, comes to the fore. In this paper, we consider the incentives for efficient content placement in a global content oriented network. We argue for a model of the content placement decisions made by transit ISPs as a cooperative game, and present a Shapley-value based mechanism to incentivize ISPs to place contents efficiently. We argue that with such a mechanism, ISPs have incentives both to cooperate to maximize surplus, and to employ placement strategies aligned with the global welfare. Our simulations give preliminary evidence that our proposed mechanism could profitably be applied in the near-term Internet, and based on extrapolations of some widely observed trends, become even more profitable for ISPs on longer time horizons.**

I. Introduction

Today's networking landscape is at an interesting cross-roads. While it is apparent that *content* is the dominant factor driving network usage by end-users, neither the underlying Internet architecture, nor the business models of most ISPs, are aligned to provide the most efficient (and profitable) content delivery mechanisms. As we discuss below, in both contexts, the reasons appear to largely be historical, and in all likelihood, this period of non-alignment is a transient one. Therefore, a key question, and the focus of our work, is to reconsider the economics of content hosting and content delivery as this transitionary period comes to a close.

From an architectural perspective, the move towards a content-driven usage model was never adequately supported by the underlying host-based paradigms underlying the architecture of the Internet. As a result, hosts, applications, and providers have had to construct workaround solutions to enable more efficient access to, and delivery of, content. These range from applications such as peer-to-peer networks to facilitate content transfers [14], [22] to content delivery networks controlled by management software to serve hosted content from locations close to end-hosts [4], [23]. While debating the merits of future Internet architectures is beyond the scope of this paper, it is noteworthy that numerous recent proposals [20], [15], [5] either elevate content explicitly to the center of the network, or provide first-class support for content. These approaches benefit content in many ways, such as by giving content self-certifying names, by making content routable, and by making content security intrinsic and explicit.

From an economic perspective, the historical evolution of how ISPs have handled content has also been a muddied one. In the past decade, transit ISPs have been caught in the middle between publishers and consumers of content, and have largely been ineffective at shaping the various debates about content (such as network neutrality [11] and content pricing models [16]). At the same time, while the standard ISP business model of being paid to transit bits has struggled, emergent content delivery networks such as Akamai and Limelight have built massive overlays on top of the ISPs, that have opportunistically taken advantage of the rise of content, arguably at the ISPs' expense. The potential unsustainability of this has recently come into focus, as traditional ISPs such as AT&T and Level3 have begun to build out their own CDNs, or have moved closer to a CDN model themselves [1], [2].

At this point, the stage is set for our discussion. We assume that content will continue to be a dominant type of traffic; that future network architectures will have evolved *native* methods to name, route and deliver content; and that future ISPs will have an opportunity to interact more deeply with content, such as by content hosting, and content placement.

Today's Internet is a collection of networks operated by different ISPs, each operating according to its own best interests. ISPs are generally taxonomized into three classes [26]: content, eyeball and transit ISPs, in which content ISPs specialize in hosting content publishers, eyeball ISPs support the last-mile delivery to residential users, and transit ISPs connect content ISPs with eyeball ISPs. The incentive of placing contents for an eyeball ISP is obvious because it can avoid paying transit networks by delivering the contents from a copy placed inside it; strategies for content management inside a content ISP are also well understood. Our focus is therefore on incentives for future transit ISPs, where the most significant bandwidth savings can be achieved (as opposed to the naive baseline approach of transiting bits).

A key challenge in a content-oriented network is to align incentives so that efficient content placement can occur more naturally. After all, content placement benefits transit ISPs by saving bandwidth in two ways: it enables faster delivery of content to eyeball networks directly, and it enables more efficient dispatching of content (recursively) to other transit ISPs. However, incentives for transit ISPs to place contents are not always present under today's Internet infrastructure: intuitively, due to storage and associated hosting costs, an

ISP would not keep contents for a time span longer than as needed to receive and forward them. Furthermore, depending on the structure of their peering agreements, transit ISPs may find it more profitable to forward, rather than store bits. Also, digital rights management and network neutrality factor in to ISPs' decisions regarding the hosting and, albeit indirectly, prioritization of some content over others. Lastly, transit ISPs face competition from other entities, for instance, content delivery networks, that may further perturb their incentives.

We argue that the key to unlock the benefits produced by content oriented network for transit ISPs is to minimize their distribution cost to improve performance, offer competitive price and maximize their surplus. Some degree of cooperation between the transit ISPs may also be needed (or at least, continuing to operate as if this is a non-cooperative game may backfire). In such a setting, mechanisms that appropriately measure each transit ISP's contribution in providing content placement, and compensating them commensurately, is needed to provide appropriate incentives to transit ISPs.

In this paper we consider such an incentive mechanism. We model the content placement of transit ISPs as a cooperative game and apply the Shapley value [24] solution concept to develop a candidate profit distribution scheme. By analysis and simulation, we provide preliminary evidence that our mechanism provides appropriate incentives for transit ISPs to place contents that optimize the network's distribution cost; moreover, these incentives are likely to become stronger over time, based on extrapolation of current Internet trends.

II. Related Work

Content placement is a broad area that spans theoretical and systems research. Instead of cache replacement mechanisms performed on an isolated cache, this line of research focuses on strategies and protocols to deploy contents to improve the performance of the whole system. Since the concept of optimal data placement was introduced [12], many efforts have been made in both theoretical and system perspectives. In [6] it was shown that the general data placement problem is APX-hard, and approximation algorithms for special cases were presented and analyzed; in [8] the general data placement problem was tailored to real system environments and requirements, for which a constant approximation distributed algorithm was designed. In [21] the problem of optimally replicating contents for a content distribution network (CDN) was considered, and several heuristics were presented and evaluated; in [7] the idea of combining caching and content replication was presented.

With the proposal of content oriented networks, economic incentives caught the attention of network research community recently. In [28], it was pointed out that existing incentive mechanisms were unsatisfactory; in [19] the choices of cache sizes by individual proxies was modeled as a game, and incentives of optimal resource allocation was discussed; in [3] the flow of transmitting contents was modeled, in which entities in different positions were analyzed, and their incentives of caching were derived.

The Shapley value is a classical solution concept in cooperative game theory (see Section IV). There have been numerous research on axiomatization [18] and representation [17] of the Shapley value. Recently, it has been applied to the economic aspects of networking: in [25] the problem of inter-domain routing was considered, serving as incentives for ISP to connect to other ISPs and to route traffic in a better way than hot-potato routing practiced by most ISPs nowadays; in [26] it was used to distribute profits among different types of ISPs, and simple closed-form calculation method for the Shapley value was presented; in [27] it was used to encourage participation in peer-assisted services, and a simpler way to calculate the Shapley value was shown for this case.

III. System Model

Our model of the overall networked system consists of two parts: a network model and a model for how ISPs define and derive utility, revenue, and profits.

A. Network Model

Given a network $G = \{V, E\}$, in which V is the set of routers and E is the set of links. Each router $v \in V$ is annotated with its capacity reserved for contents (μ_v) and the ISP it belongs to (Ψ_v) (a router belongs to one ISP). Each link is annotated with its distance. For any pair of routers u and v, there is a path $p_{u,v}$ to carry traffic from u to v.

Assume that the set of all ISPs is N, define a coalition S, $\emptyset \subset S \subseteq N$, to be a set of ISPs which collectively provide transit service. From the topological perspective, the subnetwork G_S induced by a coalition S is $G_S = \{V_S, E_S\}$, in which $V_S = \{v|\Psi_v \in S\}$ and $E_S = \{(v_1, v_2)|v_1, v_2 \in V_S\}$.

Let $R^S(u, v) = 1$ if v is reachable from u in G_S, i.e. there exists a sequence of routers $< u = n_0, n_1, \ldots, n_m = v >$ such that $(n_i, n_{i+1}) \in E_S$ for all $0 \leq i < m$ (and the path from u to v in G_S is denoted as $p^S_{u,v}$); otherwise $R^S(u, v) = 0$.

Let C denote the set of contents to be transited. Denote a transmission by $T^c_{s,t}$, of content $c \in C$ from source s to client t. Let ν_c denote the size of content c. A transmission happens as follows: a request is sent from t to s along $p^S_{t,s}$ requesting a content c. c may be placed at some routers along the path based on the content placements of routers. Assume router r has the content ($r = s$ if c is not placed along $p^S_{t,s}$), the request is served from r to t.

B. Utility Model

We model three parts of utility: revenue of transmissions, transmission costs and storage costs for replicated contents. Note that these components are defined for valid transmissions, i.e. $T^c_{s,t}$ such that $R^S(s, t) = 1$, otherwise they are 0.

revenue: assume that for every transmission $T^c_{s,t}$, a certain amount of revenue $r^c_{s,t}$ is generated to the coalition involved in the transmission. The amount of revenue is the result of the negotiation between the coalition of transit ISPs and content, eyeball networks. In the short term, it is independent of where the content is actually delivered. However, in the long run it depends on where contents are delivered: when a coalition decides how much it should charge for a transmission and making itself competitive in the market, cost associated to the transmission is an important factor to be considered.

transmission cost: if a transmission $T^c_{s,t}$ is served at router r, we model the transmission cost σ_1 as proportional to "bit-miles", a reflection of the bandwidth-delay product of the transmission that takes place: $\sigma_1(T^c_{s,t}) = \nu_c l(r,t)$, in which $l(r,t)$ is the network distance from router r to t along path $p^S_{r,t}$. We omit the cost of transmitting the initial request of the content as the request is relatively small in data size.

storage cost: Assume that each router updates its content placement at every time interval τ. Let binary variable $P^\tau(c,r)$ denote whether content c is placed at router r during τ. The storage cost of c during period τ is $\sigma_2^\tau(c) = \beta P^\tau(c,r)\nu_c$, $\beta \in R$. [1]

Now we define the utility of a coalition S. Let T_S be the set of transmissions served by S and C be the set of contents in these transmissions. The transmissions are served within subnetwork G_S. The utility of coalition S is defined as

$$V(S) = \sum_{T^c_{s,t} \in T_S} R^S(s,t)(\alpha r^c_{s,t} - \nu_c l(r,t)) - \sum_{c \in C} \sum_{r \in V_S} \beta P(c,r)\nu_c \quad (1)$$

in which $\alpha, \beta \in R$.

We now formulate the key problem in this work, the content placement problem:

Problem 1: The *content placement problem* facing a coalition S (or as a special case, an ISP) is to place contents (determining $P(c,r)$) for each $r \in V_S$ such that $V(S)$ is maximized, while respecting capacity constraints, i.e. $\forall v \in V_S$, $\sum_{c \in C} P(c,v)\nu_c \leq \mu_v$.

In a centralized sense, this problem is NP-hard and hard to approximate [6]. Our focus, however, is not an optimal solution to this problem. Instead we reason about it from the standpoint of cooperative games, and consider how the use of different heuristics and coalitional strategies could be employed by sets of strategic players in practice.

IV. Content Placement as a Cooperative Game

In this section, we model content placement as a cooperative game across ISPs. We begin with the necessary background for our approach: the framework for cooperative games, various definitions used in defining solution concepts, and the Shapley value profit sharing mechanism. We then demonstrate how to apply these methods to the problem setting in our model.

A. Background: Cooperative Games and the Shapley Value

In a cooperative game framework, a set of n players form coalitions $S \subseteq 2^n$ that cooperatively generate profits and share those profits amongst the members of the coalition. A valuation function V maps a coalition to a real-valued utility $V : 2^n \rightarrow \mathbb{R}$. The profits need to be shared fairly among the coalition members. An axiomatic definition of equitability and a mechanism for fairly dividing payoffs was the solution concept developed by Shapley in 1958 [24]. While Shapley's properties were different from the three listed below, these three are more intuitive and lead to the same unique mechanism [18].

Letting $\varphi_i(N,V)$ denote player i's share of profit in a set of players N where the utility function is V, the axioms are:

1) *Efficiency*: $\sum_{i \in N} \varphi_i(N,V) = V(N)$.
2) *Symmetry*: If for all $S \subseteq N \setminus \{i,j\}, V(S \cup \{i\}) = V(S \cup \{j\})$, then $\varphi_i(N,V) = \varphi_j(N,V)$.
3) *Strong monotonicity*: Given (N,V) and (N,W), if for all $S \subseteq N \setminus \{i\}$, $V(S \cup \{i\}) - V(S) \geq W(S \cup \{i\}) - W(S)$, then $\varphi_i(N,V) \geq \varphi_i(N,W)$.

Intuitively, these properties ensure that the mechanism should distribute all the profit, it should be fair in the sense that players with the same contribution to the coalition receive the same profit; and finally, contributing more to the coalition leads to more profit for a player. Mathematically, the Shapley value is defined as each player's average marginal contribution over all possible orderings of players:

$$\varphi_i(N,V) = \frac{1}{|N|!} \sum_{\pi \in \Pi} (V(S(\pi,i) \cup \{i\}) - V(S(\pi,i))) \quad (2)$$

where $S(\pi,i)$ denotes the subset of players preceding i in ordering π, Π is the total orderings of N, $V(.)$ is the profit generated by the corresponding set of players.

B. The Content Placement Game

Returning to our problem, intuitively, an ISP benefits from participating in coalitions for cooperative content placement because:

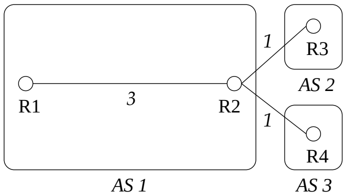
1) An ISP can utilize the replicated contents at other ISPs' routers to serve its customers (eyeball networks).
2) One copy of replicated content can serve multiple transmissions, thus utilizing the storage to the best extent.
3) Cooperative content placement allows improved content layout, prevents less valued replication and enables more contents to be placed in the network.

Framed as a cooperative game, each individual member in the coalition strategizes on how to place contents according to the utility function described and defined in Section III. We define *content placement of ISP* i in coalition S, denoted by P^S_i, as the contents selected by ISP i: $P(c,r)$ for each $r \in V_S$ such that $\Psi_r = i$. Among all possible placements P^S_i, we define the *coalitionally optimal placement strategy* of ISP i, denoted by $\hat{P}^S_i$, as the placement that maximizes $V(S)$. Similarly, we define P^S and $\hat{P}^S$ to be the content placement of coalition S, and the coalitionally optimal such placement, respectively.

C. Content Placement Strategies

We now briefly consider some candidate heuristic content placement strategies that ISPs might employ, and outline algorithms to determine content placement.

[1]Note that since the utility is additive over time intervals, we consider transmissions within one time interval and drop τ in the utility function.



	$S' = \{$AS 1, AS 2$\}$	$S' = \{$AS 1, AS 3$\}$	$S' = \{$AS 1, AS 2, AS 3$\}$	Shapley Value
Case (1)	Replicated at $R3$ $V(S') = 2$	Replicated at $R4$ $V(S') = 2$	Replicated at $R2$ $V(S') = 5$	$(2.33, 1.33, 1.33)$
Case (2)	Replicated at $R3$ $V(S') = 2$	Replicated at $R4$ $V(S') = 2$	Replicated at $R3$ and $R4$ $V(S') = 4$	$(2, 1, 1)$
Case (3)	Replicated at $R3$ $V(S') = 2$	Replicated at $R4$ $V(S') = 2$	Replicated at $R3$ and $R4$ $V(S') = 4$	$(2, 1, 1)$

TABLE I
EXAMPLE OF CONTENT PLACEMENT STRATEGIES AND THE SHAPLEY VALUES

1) Content Placement Strategies: Consider the following intuitive content placement strategies, in which we use the term *candidate set* to denote the content feasible for a given ISP to place.

Coalitionally Optimal Placement: Each ISP's content selection is aligned with the optimal strategy of the coalition, i.e. if content c is placed at R in $\hat{P}^S$, it is also at R in $\hat{P}_i^S$.

Aggressive Placement: Each ISP replicates contents if and only if doing so reduces transit cost. Any request reaching a router that has a copy of the content terminates at that point. Note that if a request is served at a Content-Store, it will not pass through subsequent routers along the path. If every router performs aggressive placement, the optimization decision becomes more myopic: for instance, a router as the potential role of an internal distribution node may find placing some contents not worthy enough due to aggressive placement of other routers, which choose to place the contents albeit with a relatively small reduction of transit cost. The system ends up with sub-optimal placement for these contents.

Myopically Selfish Placement: candidate set of ISP i only contains transmissions whose destination routers belong to i (in the context of a transit network, a destination router is the router through which the content is delivered to the eyeball network). This strategy is similar to today's application-specific content delivery approach: an application often rents servers and selects contents to be placed at those servers.

2) Content Placement Algorithms: We start with centralized approaches to determine content placements. Assume that each router has information on sizes and frequencies of the contents that pass through it, i.e. the aggregated access demand for each content is known.

Optimal and Selfish Placements: consider the optimization problem stated in Section III. Since it is APX-hard, a natural approach is to employ a hill-climbing heuristics to improve the utility of content placement. We start with no content in the whole network and apply iterative best-response. We consider two operations in each iteration: (1) associating and (2) disassociating a content with a router. the former for every content in every router's candidate set and the latter for every placed content in the network. In each iteration, we choose the operation that maximizes the reduction in cost, until no such move exists. Note that for each router, there may be many transmissions associated with a content, in which case the total cost changes in proportion to the number of transmissions it services, but the storage cost is counted once.

For optimal placement, a content is in the candidate set of a router if the following criteria are met: (1) the router is on the path of the transmission; (2) no prior hops have placed the content; (3) the router has sufficient capacity to place the content. For myopically selfish placement, the destination of the transmission must additionally belong to that same ISP.

Aggressive Placement is more naturally a decentralized process: if synchronization is assumed, the process of each content request traveling from the source to the destination can be easily simulated. When a request reaches a router, the router evaluates the benefit of placing the content. Each router's objective is to fill up its capacity and achieve the largest benefit, in the spirit of a Knapsack problem.

3) Example of Content Placement Strategies and the Shapley Values: Table 1 shows an example of the Shapley values under different content placement strategies in a very simple network setting. The network topology is shown in the figure (left) with AS numbers, router identifiers and link lengths. There are two transmissions of the same file with unit size, one from $R1$ to $R3$ and the other from $R1$ to $R4$. We assume that each transmission generates a revenue of 5 for the whole network. The storage cost at every router is 3. Let $\alpha = \beta = 1$. Assume that all routers have sufficient space to replicate the file. Consider the cases in which ISPs employ (1) optimal placement, (2) aggressive placement and (3) selfish placement. The placement of each case, the utility of each subset (with positive utility) and the Shapley value for each ISP are shown.

Consider the above strategies in the case of the coalition consisted of all ISPs: the optimal placement is to place the content at $R2$ to achieve a total profit of 5 (10 total revenue, less 3 for storage at router $R2$ and 1 each for transmitting to $R3$ and $R4$ respectively); in the case of aggressive placement, consider the request from $R3$: since compared to not doing so, replicating the content at $R3$ reduces the distribution cost by 1, $R3$ chooses to place the content; same for the request from $R4$; in the case of selfish placement, since $R2$ does not consider contents that are not delivered to its ISP (AS 1), only $R3$ and $R4$ consider placing the content, so the result is the same with the case of aggressive placement strategy.

D. Equilibrium of the Content Placement Game

In the example shown in Table 1, each ISP maximizes its profit by employing optimal placement strategy. The following generalized theorem can be proved following from the Shapley value solution concept:

Theorem 1: Under the Shapley value mechanism, the optimal placement strategy of coalition $\hat{P}^S$ is a Nash Equilibrium.

Proof: By contradiction. Assume that AS i can make more profit by deviating from optimal placement strategy, then there must exist a coalition S' ($i \notin S'$) such that $V(S' \cup \{i\}, \hat{P}_i^{S'}) - V(S') < V(S' \cup \{i\}, P_i^{'}) - V(S')$, in which $\hat{P}_i^{S'}$ denotes the content placement of i aligned with $\hat{P}^{S'}$, the optimal placement strategy of S', $P_i^{'}$ denotes the content placement strategy AS i deviates to, and $V(S, P_i)$ denotes the utility of S if AS i employs strategy P_i.

This contradicts the fact that $\hat{P}^{S'}$ is the optimal strategy for S'. ■

E. Decomposition of the Shapley Value

Returning to the utility function $V(S)$: because $l(s,t) = l(s,r) + l(r,t)$, $V(S)$ can be written into two components: $V(S) = V_X(S) + V_Y(S)$, where:

$$V_X(S) = \sum_{T_{s,t}^c \in T_S} R^S(s,t)(\alpha r_{s,t}^c - \nu_c l(s,t))$$

$$V_Y(S) = \sum_{T_{s,t}^c \in T_S} R^S(s,t)(\nu_c l(s,r)) - \sum_{c \in C} \sum_{r \in V_S} \beta P(c,r) \nu_c.$$

$V_X(S)$ can be construed as the revenue of coalition S without content placement, $V_Y(S)$ is the reduction of cost if content placement is implemented. The corresponding Shapley value can also be decomposed into two parts (directly from the additivity property of Shapley value [24]): $\varphi_i(S, V_X)$ and $\varphi_i(S, V_Y)$, denoting the Shapley values of ISP i from $V_X(S)$ and $V_Y(S)$ respectively.

V. Simulation Results

A. Simulation Settings

To instantiate the network system in Section III, we need to provide a network topology and representative workloads. We choose as follows:

1) Network Topology: Router-level ISP topologies are widely viewed as proprietary, and are not publicly available. We therefore use datasets measured by RocketFuel [29], a project that infers router-level topologies from measurements. There are 6 major US ISPs in the RocketFuel dataset: ASes 6461, 3967, 3356, 1239, 2914 and 7018. In the RocketFuel dataset, each router has the following information: geographical location and measured connections to other routers (of the ISP it belongs to and other ISPs). We coalesce routers in a certain geographical location into Points of Presence (PoPs). The capacity of a PoP is proportional to the number of routers in it. An inter-PoP connection (a link between a pair of PoP) exists if a connection exists between two routers located in these two PoPs respectively. Note that both links inside a single ISP and AS-AS links are contained. Link distance is approximated by the Euclidean distance between the geographical locations of its two endpoints. Network distance between a pair of PoPs is the sum of the distances of links that constitute the path.

Paths are calculated for each possible coalition using standard routing algorithms: Dijkstra's algorithm for intra-domain routing; standard BGP preference for inter-domain routing: a path crosses as few ISPs as possible. Among paths that cross the fewest ISPs, the path with the shortest network distance is chosen. Now we have a topology for each possible coalition, in which each PoP is annotated with its affiliation of an ISP, its capacity, geographical location, connections to its neighbors and routes to all other PoPs.

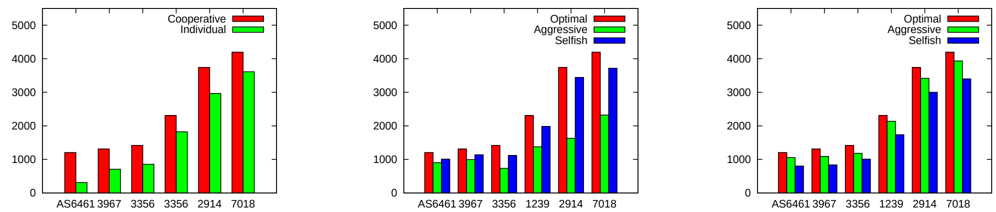
2) Workload: The basic information needed to drive our pilot study is an aggregated workload within a certain time span, i.e. a set of transmissions of files. Furthermore, we need to associate these transmissions to the PoPs. Among many workload characterization efforts, we chose ProWGen[9], a web workload generator tailored for the study of cache performance at servers. For parameter settings, we used the empirical settings from Web traffic characterization: file sizes follow a Lognormal Pareto distribution (the percentage of files at the tail is 30%, the heavy tail index is 1.1); access frequencies follow a Zipf distribution (the Zipf slope is 0.75); frequency and file size is uncorrelated. An access of a file constitutes a transmission.

We associate the generated transmissions to PoPs in the following way: in each ISP we choose a PoP as a publisher. Each file is hosted by a publisher at random. For each file, we distribute its access to clients: each time a client (a PoP) other than the publisher is chosen randomly along with its access frequency from this client, and this frequency is deducted from the total number of access for this file. This process is repeated until the number of access for this file is 0. Finally, we set a targeted number of transmissions for each ISP which is proportional to its size. If the number of transmissions allocated to an ISP exceeds this target, client will not be chosen from it.

3) Parameter Settings of Our Model: As shown in Section IV-B, the Shapley value of an AS i can be decomposed to two parts: $\varphi_i(V_X)$, which is independent of content placement; and $\varphi_i(V_Y)$, which depends upon placement. In this section we focus on $\varphi_i(V_Y)$ for all ISPs. So the choice of α does not have influence on ISPs' content placements. We will show the effects of β in our simulations. In each setting we run the content selection algorithm for each content placement strategy, calculate the utility defined in Section III and each ISP's share of profit.

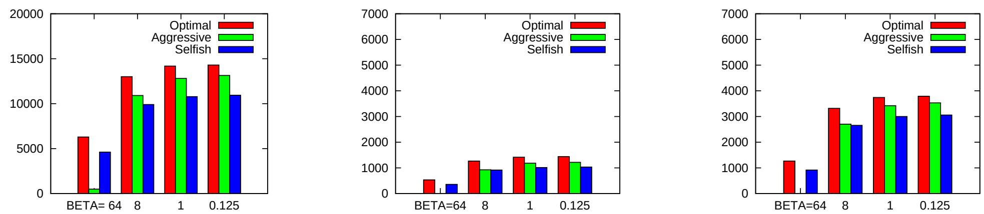
B. Comparisons of Different Placement Strategies

Figure 1 shows the profits of different placement strategies for each ISP. In these plots, the sum of profits across ISPs can be interpreted as the overall system utility, or equivalently, the overall cost-effectiveness of the network. In (a) we contrast the profit each ISP can make alone with that in a collaboration in which ISPs employ optimal placement strategy; in (b) we show the Shapley values when an ISP unilaterally deviates from the optimal placement strategy (yet shares in the Shapley payout); in (c) we show the Shapley values when all ISPs employ the same placement strategy. From these plots, cooperation is



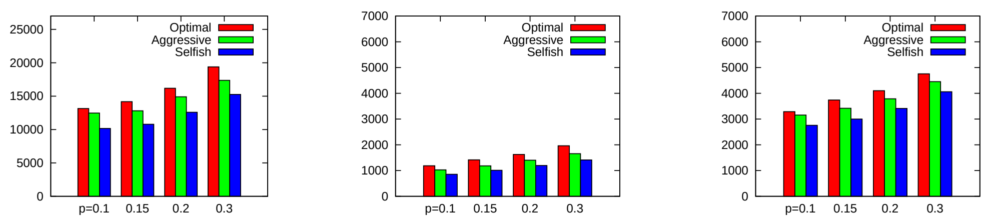
(a) Cooperative and individual profit (b) Unilateral deviation from optimal (c) ISPs employ the same strategy

Fig. 1. Profits: comparison of different strategies ($\beta = 1$)



(a) Total utility (b) Shapley value of AS 3356 (c) Shapley value of AS 2914

Fig. 2. Profits when β changes



(a) Total utility (b) Shapley value of AS 3356 (c) Shapley value of AS 2914

Fig. 3. Profits when p changes

clearly beneficial, and coalitionally optimal placements derive the most surplus. When all ISPs employ the same strategy, aggressive placement is better than selfish placement because of its inherent adaptivity to minimize costs. In comparison, if ISPs unilaterally deviate from optimal placement, the disturbance to the optimal placement solution caused by aggressive placement is significant and harmful. The case of selfish placement is the opposite: when only one ISP is selfish, the overall content placement is still near optimal; while when all ISPs are selfish, the decrease of overall utility, as well as each ISP's share, is more significant.

In our model, β is a parameter that describes the relative cost of storage. In Figure 2 we show the total utility of the network and the Shapley values of two representative ISPs (a large AS: 2914 and a smaller AS: 3356) under different strategies with different settings of β. In each experiment all ISPs employ the same strategy. We can see that although β is a factor that influences profits, the profits stabilize when β is small enough. This is evidenced by cases where $\beta = 1$ and $\beta = 0.125$: some contents are not frequently transmitted, or the source-destination pairs do not make content placement along the path valuable. We can also see that if storage is expensive, it is particularly unfavorable to employ aggressive placement: from whole network's perspective, the precious resources are not utilized properly due to the aggressive ISP's content selection. However, for selfish placement, when the storage cost is high, it is harder to contribute, and the loss of profit is less significant.

C. Future Trends

We now return to our initial motivation, the future Internet. While we cannot predict the future, several basic and long-observed trends, such as Moore's law, are likely to continue to apply. We consider how our incentive mechanism would perform, in a hypothetical world in which those trends continue, relative to today.

Although Moore's law was first used to specifically describe microprocessor transistor counts, it has many counterparts in the digital technology world: related to our model, storage cost halves, transmission cost halves, and capacity doubles. Also these laws lead to the prevalence of large files. While this is a complicated setting, most scenarios are straightforward and can be reduced to the scenario in which workload changes while other factors remain. We focus on such a setting:

changing p, the percentage of the files that are in the tail of the Lognormal Pareto distribution of file sizes.

We show the overall utility and the Shapley values of two ISPs in Figure 3 as we vary p. Generally, as p increases, ISPs get more profit by optimally placing contents, and the difference between optimal placement and other strategies increase. Our intuitive explanation is that when more large files are frequently accessed, placing them optimally becomes more profitable.

VI. Discussion

Looking forward, several important challenges with our proposed mechanism remain. Key among these are how to incorporate these methods into an ISP's infrastructure while retaining appropriate economic incentives, and dealing with additional technical issues. We discuss these now.

A. Application Architectures

In today's Internet, ISPs often employ caching: temporarily storing contents to facilitate future transmissions. In the context of CDNs, providers go beyond caching to content placement via replication. We argue that combining the ideas from these two lines is feasible and beneficial. Instead of driven only by instantaneous user requests, ISPs should consider the longer-term value of content placement. From a system-wide perspective, efficient content placement can complement caching mechanisms by providing hints, and can potentially limit churn associated with frequent updates caused by caching. Indeed, a similarly integrated approach appears as the Content-Store proposed in [20]: buffer memory used to replicate content to facilitate content-based routing. Informed by which contents benefit most from replication, each router can optimize the Content Store accordingly. It is feasible because it does not require significantly more computation than current content delivery approaches (arguably less); it is beneficial because it is aligned with ISP's incentives in both profits and performance.

One possible application architecture is that a coalitional entity, similar in spirit to a CDN of today, calculates the optimal content placement periodically and sends the results as caching hints to either every router or to a delegate for every ISP. Shapley values can be calculated by this entity.

Note that there may be many practical considerations beyond our simplified model, but can be considered under the same framework: for instance, in addition to content placement, an ISP may strategically determine cache size at each router to reduce its operational cost; an ISP may also engineer its traffic to route contents towards the desired routers to adapt to such optimal cache sizes. These are more complicated optimization problems considered by ISPs, however, the incentive mechanisms for them to place contents optimally remain.

B. Decentralizing Content Selection

Another possible but challenging approach is to decentralize content selection process and the associated profit reporting and calculation mechanism. The major issue is dependency: assume that a transmission follows the path $u_1 \sim u_2 \sim u_3$. The content selection of u_2 depends on that of u_1: when content requests are served by u_1, they will not reach u_2. However, there may be cases in which this greedy choice is suboptimal; moreover, time synchronization issues can lead to race conditions, in which case routers' content selections may need to be done interdependently.

Based on the assumption that inputs used to make content selection do not change dramatically during a relatively short period of time, periodic synchronization can be used to update the inputs: for each content, the router that has the content sends a message towards the publisher. The message has the information on how many requests were served and how much cost was reduced since last synchronization. Upstream routers can then easily coordinate with downstream routers as to placements that maximize cost reductions. Note that when this mechanism is applied across coalitions, truthful information reporting from participating ISPs is required.

Finally, if content selection is decentralized, the placement still needs to be reported to a central entity, which gathers the information and calculates the Shapley value for each ISP; or the Shapley value is calculated recursively amongst ISPs. The former approach is contingent on truthful information reporting; the latter approach is preferable, but seems challenging. In the context of our problem, although the Shapley value can be defined recursively [17], it is still defined over all possible subsets and requires significant calculation.

C. Other Practical Issues

1) Shapley Value Calculations: It was widely understood that computing the Shapley value exactly requires calculating the contribution of each ISP on every possible ordering of every subset, which has exponential time complexity. If a central entity is dedicated to it, it is not infeasible because in the core of the Internet the number of transit ISPs is relatively small. Furthermore, there are several ongoing efforts on approximating the Shapley value in polynomial time based on linear approximation [13] or sampling [10] that may prove suitable for our work.

2) Coalitions on Today's Internet: Our simulation showed the case in which the network is comprised of several core transit networks. In practice, a coalition does not necessarily have to be the whole network: depending on the workload and network structure, some workloads on some ISPs do not have material influence on profit made by other ISPs with different workloads. Also, some ISPs can be delegates of their customer stub ISPs. These cut points also help reducing the complexity of calculating the Shapley value.

There is also a potential gap between coalitions and the current bilateral peering structure. In the core of the Internet, most ISPs form peer-to-peer relationship to exchange bulk traffic, which is not necessarily geared towards profit maximization. However, most stub networks connect to the Internet through a provider ISP, which makes profits from its customers. The interplay between coalition-induced profit, customer-induced profit, and bilateral agreements needs to be studied.

3) Information Reporting: In order to assess the Shapley value of an ISP, its internal router-level information is needed. ISPs typically do not disclose this type of information to the full level. In the context of our problem, the information needed is: the capacity of Content-Store enabled routers (or data centers near routers) and network distances between each pair of them. An ISP can make some structurally important routers Content-Store disabled and increase the difficulty of inferring router-level topology by pairwise information.

The Shapley value mechanism and the distributed content selection also require truthful information. Audit trail mechanisms need to be designed to prevent ISPs from misreporting. Promisingly, future content oriented networks have focused both on intrinsically secure content delivery design, and also hold out the promise of facilitating manageable accounting mechanisms [20], [15].

VII. Conclusion

In this paper we proposed employing a Shapley value based profit distribution mechanism to incentivize ISPs to cooperatively place contents inside a content oriented network. We showed that our mechanism has promise for utility maximization via simulations drawn from traces driven from measured network topologies and representative workloads. We discussed issues regarding deploying mechanisms such as this on the Internet, from the favorable: technological and network-architectural trends, to the more challenging, such as economic considerations. We believe that progress on those problems will advance the economic incentives of ISPs as well as mechanism design, both from a systems aspect and a theoretical aspect.

References

[1] http://www.business.att.com/enterprise/Portfolio/content-delivery/.

[2] http://www.level3.com/en/products-and-services/video/cdn/.

[3] P. Agyapong and M. Sirbu. Economic incentives in content-centric networking: implications for protocol design and public policy. In *39th Telecommunications Policy Research Conference*, Arlington, VA, 2011.

[4] Akamai Technologies. http://www.akamai.com.

[5] A. Anand, F. Dogar, D. Han, B. Li, H. Lim, M. Machado, W. Wu, A. Akella, D. Andersen, J. Byers, S. Seshan, and P. Steenkiste. XIA: an architecture for evolvable and trustworthy Internet. In *Proceedings of Hotnets 2011*, Cambridge, MA, 2011.

[6] I. Baev and R. Rajaraman. Approximation algorithms for data placement in arbitrary networks. In *Proceedings of SODA*, 2001.

[7] S. Bakiras and T. Loukopoulos. Combining replica placement and caching techniques in content distribution networks. *Computer Communications*, 28:1062–1073, 2005.

[8] S. Borst, V. Gupta, and A. Walid. Distributed caching algorithms for content distribution networks. In *Proceedings of INFOCOM 2010*, San Diego, CA, 2010.

[9] M. Busari and C. Williamson. ProWGen: a synthetic workload generation tool for simulation evaluation of Web proxy caches. *Computer Networks*, 38:779–794, 2002.

[10] J. Castro, D. Gomez, and J. Tejada. Polynomial calculation of the Shapley value based on sampling. *Computers and Operations Research*, 36:1726–1730, 2009.

[11] A. Dhamdhere and C. Dovrolis. Can ISPs be profitable without violating "network neutrality"? In *NetEcon '08*, Seattle, 2008.

[12] L. Dowdy and D. Foster. Comparative models of the file assignment problem. *ACM Computer Surveys*, 14:287–313, 1982.

[13] S. Fatima, M. Wooldridge, and N. Jennings. A linear approximation method for the Shapley value. *Artificial Intelligence Journal*, 14:1673–1699, 2008.

[14] Gnutella. http://rfc-gnutella.sourceforge.net.

[15] D. Han, A. Anand, F. Dogar, B. Li, H. Lim, M. Machado, A. Mukundan, W. Wu, A. Akella, D. Andersen, J. Byers, S. Seshan, and P. Steenkiste. XIA: Efficient support for evolvable Internetworking. In *Proceedings of NSDI 2012*, San Jose, CA, 2012.

[16] P. Hande, M. Chiang, R. Calderbank, and S. Rangan. Network pricing and rate allocation with content provider participation. In *Proceedings of INFOCOM 2009*, Rio de Janeiro, Brazil, 2009.

[17] S. Hart and A. Mas-colell. Potential, value and consistency. *Econometrica*, 57:589–614, 1989.

[18] H.Young. Monotonic solutions of cooperative games. *International Journal of Game Theory*, 14:65–72, 1985.

[19] A. Ip, J. Lui, and J. Liu. A revenue-rewarding scheme of providing incentive for cooperative proxy caching for media streaming systems. *ACM Transactions on Multimedia Computing, Communications and Applications*, 4(5):1–32, 2008.

[20] V. Jacobson, D. Smetters, J. Thornton, M. Plass, N. Briggs, and R. Braynard. Networking named content. In *Proceedings of ACM CONEXT '09*, New York, NY, 2009.

[21] J. Kangasharju, J. Roberts, and K. Ross. Object replication strategies in content distribution networks. *Computer Communications*, 25:376–383, 2002.

[22] Kazaa. http://www.kazaa.com.

[23] Limelight Networks. http://www.limealightnetworks.com.

[24] L.Shapley. A value for n-Person games. *Annals of Mathematics Studies*, 28:307–317, 1953.

[25] R. Ma, D. Chiu, J. Lui, V. Misra, and D. Rubenstein. Internet economics: the use of Shapley value for ISP settlement. *IEEE/ACM Transactions on Networking*, 18:775–787, 2010.

[26] R. Ma, D. Chiu, J. Lui, V. Misra, and D. Rubenstein. On cooperative settlement between content, transit and eyeball Internet service providers. *IEEE/ACM Transactions on Networking*, 19:802–815, 2011.

[27] V. Misra, S. Ioannidis, A. Chaintreau, and L. Massoulie. Incentivizing peer-assisted services: a fluid Shapley value approach. In *Proceedings of ACM SIGMETRICS 2010*, New York, NY, 2010.

[28] J. Rajahalme, M. Sarela, P. Nikander, and S. Tarkoma. Incentive-compatible caching and peering in data-oriented networks. In *ReArch '08*, Madrid, Spain, 2008.

[29] N. Spring, R. Mahajan, D. Wetherall, and T. Anderson. Measuring ISP topologies with Rocketfuel. *IEEE/ACM Transactions on Networking*, 12:2–16, 2004.