Economic Incentives in Information-Centric Networking: Implications for Protocol Design and Public Policy

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ABSTRACT

In this article, we build a simple engineering-economic model to evaluate the incentives of various network players to deploy distributed storage nodes (content stores and caches) to support information-centric network (ICN) architectures and the implications of those incentives on protocol design, industry structure and other policy issues, such as competition and network-neutrality. We find that without some explicit monetary compensation from publishers, networks will fail to deploy the socially optimal number of caches. We also study the social welfare implications of different cache deployment scenarios and identify two deployment scenarios that maximize social welfare. Finally, we show that ICN architectures provide numerous opportunities for large eyeball networks to leverage their terminating access monopoly to extract more profits from other network players. Hence, regulators must take steps to address issues such as interconnection and the role of caching infrastructure in differential quality of service provisioning in an ICN-based network architecture, in order to ensure socially desirable outcomes from their deployment.

INTRODUCTION

Many proposals for a future Internet architecture envision a widely distributed storage infrastructure within the network that facilitates delivery of content [1–5]. Such proposals, generally referred to as information-centric networking (ICN),[1] aim to address some challenges of the current Internet, such as lack of data persistence, security, and efficient in-network content delivery support [1, 3, 5]. Even though the benefits of ICN rest on the assumption of widespread storage infrastructure, such as caches and content stores on routers, previous studies fail to evaluate the economic incentives of various stakeholders to deploy the required storage infrastructure. In addition, policy issues, such as the effect of ICN on competition, network neutrality, and overall social welfare, have been largely ignored.

Recently, Trossen *et al.* [2] highlighted the importance of socio-economic issues when evaluating future Internet architectures. In addition, Clark *et al.* point out the need to identify and explicitly make provisions to deal with incentives and potentials for conflict in any network design [6]. To the best of our knowledge, Rajahalme *et al.* [7] provide the only previous analysis of the economic incentives to deploy ICN-based architectures. They qualitatively show that top-level transit providers lack incentives to deploy ICN architectures because it robs them of transit revenues. In a related work, Chun *et al.* [8] use game-theory to show that monetary payments are necessary to achieve the optimum deployment of caches within the network. However, they fail to identify the specific incentives for different types of network players because they consider a non-hierarchical network scenario.

Our work aims to fill the void in this space by providing an assessment of the economic incentives of different types of network players to partake in an information-centric network and the factors that affect these incentives. Specifically, we study the incentives of different network players to deploy storage infrastructure to support ICN and the competitiveness of different players in providing commercial caching services to publishers. We also study the social welfare implications of different cache deployment scenarios to identify those that maximize social welfare. Finally, we identify and discuss ICN protocol design considerations and policy interventions that may be necessary to ensure a desirable socio-economic outcome from deploying information-centric networks.

The rest of the article is organized as follows. We first describe our model and assumptions in the next section. We follow this with an analysis of the economic incentives of different network players to deploy caching infrastructure. Then, we evaluate the competitiveness of different network players in providing caching services and the social welfare implications of different cache deployment scenarios. We then relate our findings to the current state of the content delivery industry and discuss the policy implications and limitations of our findings. Finally, we outline

[1] In the literature, both content-centric networking (CCN) and information-centric networking (ICN) are used to describe network architectures that discover and route content based solely on the name of the desired content. In the rest of this article, we will use information-centric networking to refer to such architectures.

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Network player	Description	Examples
Publisher	Produces content for end-users	Google, CNN, eBay, Netflix
Eyeball network	Predominantly provides network access to end-users	Comcast Corporation, British Telecom
Transit network	Primarily provides transport services to publishers and eyeball networks to reach the Internet	Level 3 Communications, Tata Communications
Content distribution network (CDN)	Primarily caches and delivers content on behalf of publishers for a fee	Akamai Technologies, Limelight Networks

Table 1. *Network players considered in our model.*

how the design of ICN protocols can benefit from our findings and conclude the article.

Model and Assumptions

At its core, ICN relies on widely distributed storage within the network to facilitate delivery of content. Some authors suggest that this storage could take the form of extra memory on-board routers, usually referred to as content stores [1]. Others suggest the deployment of dedicated storage infrastructure to handle large volumes of data [2, 3, 5]. Hence, any evaluation of the incentives to deploy ICN-based architectures involves an analysis of the incentives of network stakeholders to deploy the necessary storage infrastructure to support content delivery. In the rest of this article, we will refer to both content stores and dedicated storage as caches, with the understanding that content stores will likely keep frequently requested content and other less-frequently requested content from publishers who pay a premium for content delivery. Unlike the current TCP/IP model where caches are deployed as application layer overlays, ICN assumes caches are integrated at the network layer. Thus, compared to the status quo, the relationships that exist between networks will likely change in an ICN ecosystem and alter incentives and disincentives for different network players.

In this article, we build a simple engineering-economic model, which provides a framework to analyze the incentives to deploy caches in network architectures that incorporate caching. We abstract most technical cache implementation details and account for them through the various costs incurred to provide the caching service. For instance, an architecture that utilizes numerous small caches incurs different storage, processing and bandwidth costs compared to one that utilizes a few large caches. Thus, our model can be used to evaluate the incentives to deploy caches in the current Internet ecosystem, where caches exist at the application layer. At the same time, it can be used to evaluate the incentives to deploy caches in a future ICN-based architecture, where caches exist at the network layer. It can also be used to understand incentives of cloud-based providers, who provide both storage and computation. This is possible because we can use bandwidth and interconnection costs, as well as processing and storage costs to reflect the technical differences between the different approaches.

We start with the premise that caching is beneficial to publishers and network providers, but networks will deploy the socially optimal caching infrastructure only when there is some explicit monetary compensation from publishers for doing so [8]. In our model, publishers pay separately for network access and caching services. The publisher has the option to buy network access and caching services from the same or different network providers. We identify four types of network players, namely: publishers, eyeball networks, transit networks, and content distribution networks (CDNs). Table 1 provides a description of each type of network player. Additionally, one could consider large and sophisticated publishers, such as Google, who operate an extensive backbone and caching infrastructure, as a fifth type of network player. However, we have chosen to treat such entities as publishers or CDNs, depending on whether they deploy network and caching infrastructure for their private use or for commercial purposes, respectively.

Figure 1 illustrates our network model. In general, there could be multiple networks between the eyeball network and the transit network, and the incentives for each type of transit network will be different depending on the payment flows it receives with and without caching. In the setting depicted in Fig. 1a for instance, Network A1 loses network access revenues when it performs caching but avoids bandwidth costs to transfer packets from the publisher. On the other hand, Network A2 saves on upstream transit payments when it performs caching. Due to its proximity to the eyeball network, it could even charge publishers for lower latency content delivery.

For our analysis, it is more interesting to consider transit networks that connect directly to eyeball networks. This is because publishers are likely to buy access directly from a tier 1 network that in turn serves large eyeball networks directly. Thus, we employ the simplified model in Fig. 1b in the rest of the article. Further, we refer to any transit provider that has a direct connection to an eyeball network as a transit network. Our setting eliminates the possibility of more complex network hierarchies but does not affect our conclusions about the incentives of eyeball networks, content distribution networks, and transit networks to deploy caching infrastructure and their competitiveness when they do so.

In our model, we assume that CDNs and transit networks can pay eyeball networks to locate caches directly in the eyeball network or employ high capacity links to connect external caches to multiple locations in the eyeball network in a way that makes them logically indistinguishable from caches that will be placed by the eyeball network. The latter assumption does not reflect the current interconnection model where eyeball networks pay for transit. In this case, eyeball networks prefer fewer interconnection points in order to achieve economies of scale in equipment, maintenance, and transit costs. However, multiple interconnection points become desirable for eyeball networks in an environment where they receive payments for terminated traffic. Thus, performance issues related to cache location do not form the basis of differentiation between different cache providers in our model. Rather, networks differentiate themselves through the price they charge publishers for caching services.

Additionally, we assume that publishers use a single cache provider to serve the same content to the same end-user. This reflects the current situation where publishers prefer to use a single cache provider to reduce transaction costs and benefit from economies of scale in pricing. Nevertheless, we assume that each caching provider implements internal mechanisms to achieve redundancy and load balancing. In addition, we assume the existence of a mechanism (offline or online), which enables caches to determine whether to store and deliver an object on behalf of the object's publisher. Even though the model described above does not capture all the details of the Internet ecosystem, we believe that it contains the basic building blocks necessary to make generalizable observations about the incentives of different network players in a complex heterogeneous system such as the Internet.

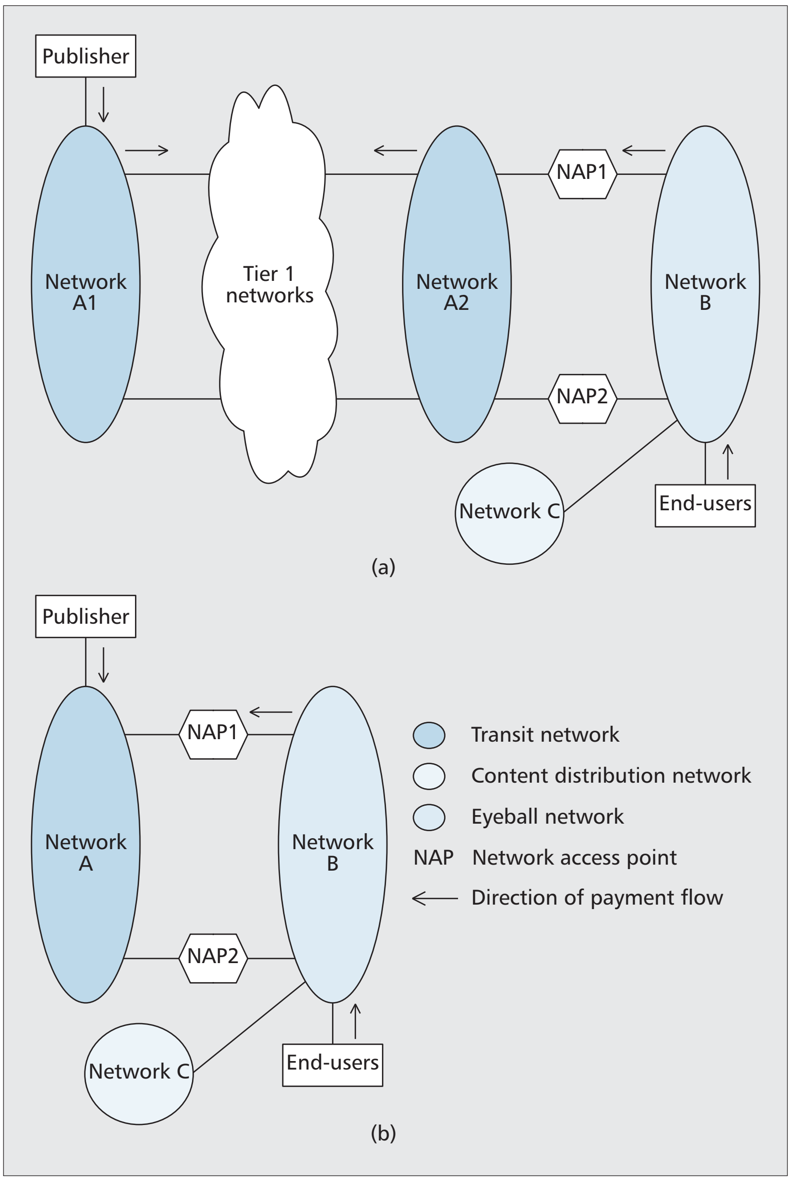

Figure 1. *Illustration of two network models. In the model in Fig. 1a, the publisher buys network access from a tier 2 network, which uses transit and peering relationships with other networks to reach the eyeball network. In the model in Figure 1b, publishers buy network access from a tier 1 transit network that connects directly to eyeball networks. In both models, publishers have the choice to buy caching services from only one of three types of network players namely transit networks (Networks A, A1 and A2), eyeball networks (Network B) and content distribution networks (Network C). Content distribution networks locate their servers and caches directly within the eyeball network (e.g., Akamai) or outside the eyeball network (e.g., Limelight). We employ the simplified model in Fig. 1b in the rest of the article: a) Multiple transit networks connect the publisher and the eyeball network; b) A single transit network connects the publisher and the eyeball network.*

Under What Conditions Will Networks Deploy Caches?

In this section we use the model depicted in Fig. 1b to investigate the incentives for network providers to deploy caching infrastructure, given various costs, inter-domain routing policies, interconnection agreements, and publishers' willingness to pay for caching services.

We limit our analysis to the delivery of a single cacheable object. This could be a single file, a collection of files usually requested together, or the contents of an entire webpage. This simplifies our analysis but does not affect the generality of our results since, in practice, caching decisions are made on individual files or objects. We model the delivery of a static or dynamic object by the storage and processing costs required. The network incurs mostly storage costs to deliver static objects from cache, whereas dynamic objects incur both storage and processing costs. Our model assumes that caches are deployed in existing network locations (e.g. edge routers, NAPs, and private peering points). Therefore, we only consider (long run) incremental costs associated with bandwidth, network access, storage, processing, accounting, and billing needed to provide caching at these locations.

In general, a publisher purchases caching services if the benefits of doing so exceed the costs. Similarly, other types of network players deploy caches when the benefits exceed the costs. We summarize the benefits and costs for the different network players in Table 2. We see from the

Network player	Benefits	Costs
Publisher	Increased revenues from improved end-user latency Resilience to flash crowds and DDoS attacks Savings in network access charges Savings in processing costs	Payment for content delivery Transaction costs to set up business relationships Costs to modify content for delivery by third-party Potential loss of content access information
Transit network	Bandwidth/transit savings Revenue from publishers for content delivery	Lost network access/transit revenue Processing costs Storage costs Billing and accounting costs Co-location and traffic termination charges
Eyeball network	Bandwidth savings Revenue from end-users due to improved latency Revenue from publishers for content delivery Co-location and traffic termination charges	Processing costs Storage costs Billing and accounting costs
CDN	Revenue from publishers for content delivery	Processing costs Storage costs Billing and accounting costs Co-location and traffic termination charges

Table 2. *Benefits and costs of deploying caches for different network players. Publishers purchase caching services from other networks and all other networks deploy their own caches.*

table that transaction costs play a significant role in determining a publisher's willingness to purchase caching services. The transaction costs for the publisher include a fixed component (e.g. finding and negotiating a contract and service level agreement (SLA) with the cache provider and modifying content to facilitate delivery by the cache provider) and a variable component (e.g. transforming content delivery reports to usable formats and dealing with problems that arise). In general, the fixed component decreases as the number of objects served from cache increases. On the other hand, the variable transaction costs increase as the number of cache providers increase.

In the current content delivery ecosystem, CDNs provide both content delivery and transaction brokerage functionality. Thus, publishers only need to worry about paying for content delivery. In the absence of an entity that plays the transaction brokerage role between publishers and different networks in an ICN-based architecture, publishers would have to enter into content delivery relationships with multiple networks. This will reduce their willingness to pay for caching services and hence the viability of paid content delivery. Therefore, it is important that ICN-based architectures institute mechanisms to facilitate the provisioning of and accounting for caching services through a single or relatively few points of contact that serve as transaction brokers between publishers and eyeball networks. A single point of contact can also aggregate content delivery reporting, thereby adding additional value for the publisher.

Furthermore, we see from Table 2 that an eyeball network obtains benefits from deploying caches, which could be significant enough to offset the costs of deployment, even without monetary payments from publishers. Eyeball networks deploy transparent caching when such significant realizable benefits from caching exist. In transparent caching, the network caches content purely for cost savings and performance improvement on its network and does not demand any form of payment from the publisher. It is done without any knowledge (or permission) from the publisher of the content.

By hosting a CDN, the eyeball network enjoys most of the benefits of caching without incurring any of the costs. Therefore, eyeball networks face an interesting decision space regarding cache deployment, which we discuss in detail later. Unlike transit and eyeball networks that obtain other benefits from caching besides the revenues from publishers, CDNs deploy caches solely for the purpose of obtaining revenue from content delivery. We see from Table 2 that large eyeball networks can use co-location and termination fees to significantly alter the incentives for CDNs. For instance, large eyeball networks can deny CDNs the permission to co-locate or charge them a high price to co-locate and terminate traffic. Smaller eyeball networks do not have such an advantageous bargaining position and would host CDNs for free or pay them in the form of free co-location, rack space, and electricity, in order to realize the benefits from caching, without deploying their own infrastructure.

Can Different Types of Networks Compete for Caching Services?

In this section we investigate the ability of different network players to compete on price for caching services and the social welfare implications of different cache deployment scenarios.

In Fig. 2 we plot the minimum payment that each network player requires to make caching economically viable for very popular objects, as a

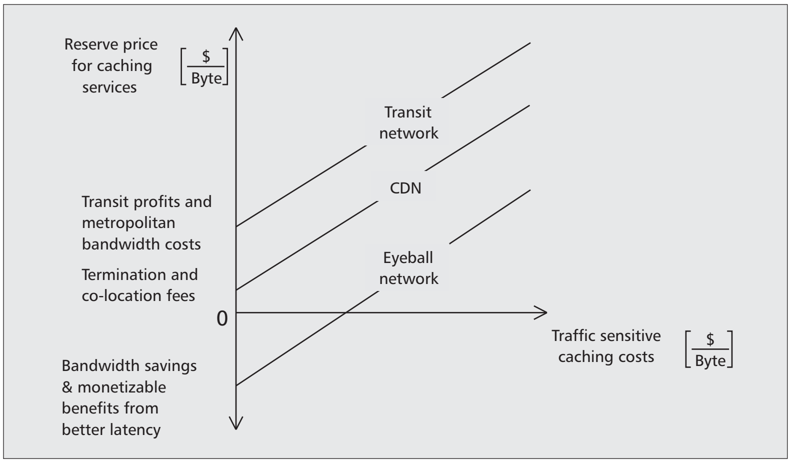

Figure 2. *Payments required by networks to make caching desirable for very popular objects when a publisher is a first-time buyer of caching services and all end-users are located in a single eyeball network. Traffic sensitive caching costs comprise per file processing, accounting and billing for content delivery. The eyeball network is in a position to charge the lowest prices for caching. This assumes that all networks obtain similar latency performance, operate caches efficiently and face the same external costs. The payment relationship between a CDN and its host network significantly affects the prices charged by the CDN. In addition, the relative position of the CDN and transit network curves depends on the exact relationship between network access charges, bandwidth costs and transit costs.*

function of the combined per file processing, accounting, and billing costs. We assume that the CDN co-locates within the eyeball network. In addition, we assume that the transit relationship between the transit network and the eyeball network remains the same when the transit network serves content from cache. This assumption reflects the fact that, in practice, the traffic flows between the two networks do not change when the transit network serves requests directly from the publisher or from a cache located in the transit network.

We have not shown the publisher's willingness to pay because it is the same for all networks when the publisher faces similar transaction costs for all networks. The publisher's transaction costs to establish a business relationship are the same for different types of networks when all end-users are located in a single eyeball network. However, when users are located in multiple eyeball networks, then the publisher incurs higher transaction costs to establish business relationships with all eyeball networks. This is because the publisher has to negotiate contracts and SLAs with multiple eyeball networks, inject traffic through multiple locations to different networks, transform multiple cache delivery report formats into a usable form, and keep track of multiple points of contact to deal with problems. In such a situation, a broker that performs all these functions on behalf of the publisher provides a means to minimize the transaction costs.

Figure 2 shows that when all networks face similar costs, the eyeball network is in a position to offer the lowest prices for caching services. Interestingly, we also see that the eyeball network does not need to invest in caching infrastructure in order to realize benefits. For instance, the eyeball network can leverage its terminating access monopoly to extract rents from a CDN by adjusting the fees it charges the CDN to co-locate and terminate traffic. Furthermore, eyeball networks can implement differential pricing of interconnection and co-location, depending on the CDN or its affiliated publishers. Nevertheless, the extent to which the eyeball network can do this is limited by prevailing transit prices (the curve for the transit network). Thus, transit pricing serves as a check on the extent to which eyeball networks can abuse their terminating access monopoly.[2]

In effect, eyeball networks can decide to invest in their own caching infrastructure, deploy limited transparent caching, and/or allow third-parties to deploy caches and appropriate some of their benefits. We illustrate the viability of cache service provisioning for an eyeball network and a CDN in Fig. 3, where we assume that a publisher's willingness to pay for caching services for a file with a relatively small update rate is the same for all networks. For simplicity, we only show a single publisher. However, in the discussions that follow, one could imagine a continuum of publishers with different willingness to pay for any file with a given popularity. The differences in publishers' willingness to pay stem from differences in processing costs, network access charges, and the revenues obtained from improved end-user latency.

In Fig. 3 the marginal cost, *MC*, for the CDN comprises per-file processing, co-location, termination, accounting, and billing costs. The net marginal cost for an eyeball network, *MC′*, is lower because it realizes bandwidth savings and increased end-user revenue from deploying caches. Strictly speaking, *MC′* decreases with increasing demand for an object because of increased monetizable benefits from improved latency. However, we assume that the monetizable benefits are exhausted at a relatively low level of demand, and are constant as demand increases further, thereby resulting in a horizontal *MC′*.

We see from Fig. 3 that in the absence of monetary transfers from the publisher for content delivery, the eyeball network will only cache objects whose popularity exceeds ϕ. Thus, the eyeball network will only cache objects in regions *II* and *IV*. The CDN will not provide any caching without monetary payments from the publisher. This suggests that networks will fail to deploy sufficient caching infrastructure in ICN architectures that lack provisions for paid caching. When mechanisms exist for payment transfers between the publisher and the network for content delivery, then pricing schemes exist that can incentivize the eyeball network to cache all objects in regions *I–IV* and the CDN to cache objects in regions *I* and *II* in Fig. 3.

An eyeball network enjoys the benefits of caching regardless of whether it deploys the caches itself or allows a CDN to deploy caches. The choice that makes sense for the eyeball network depends on two factors: the barriers to entry, and the extent to which it can leverage caching infrastructure to obtain revenue streams. The barriers to entry include capital costs to deploy caching infrastructure and access to

[2] *See [9] for a more detailed discussion of how transit pricing can serve as a check on the terminating access monopoly enjoyed by eyeball networks.*

caching technology. These barriers could be high if CDNs have a monopoly on caching technology, in the form of patents. In such a scenario, eyeball networks will likely host CDNs and use their terminating access monopoly to extract rents from CDNs in the form of co-location and termination fees. However, this creates a deadweight loss, which can be computed from regions *III* and *IV* in Fig. 3.

In the absence of significant barriers to entry, the decision to deploy caches depends on the extent to which cache ownership allows an entity to appropriate the monetary benefits from the value created in the network. We illustrate this in Fig. 4. This figure shows the realizable value for different players under different cache deployment scenarios. Strictly speaking, the value or surplus that accrues to each player is computed from the indicated area, taking into account the file size and object popularity distribution. However, in the discussions that follow, we use the area under the curves to compare the surplus (or value) since the surplus is a monotonically increasing function of the area between the curves.[3] We neglect the end-user surplus, as we assume that it remains the same regardless of the cache provider.

We see from Fig. 4a that the publisher and the eyeball network share in the benefits when an eyeball network deploys transparent caching. Even though the publisher obtains benefits in terms of transit savings, processing savings, and improved end-user latency, it loses vital information about who retrieved the content, when they retrieved it, and how they retrieved it. Hence, the publisher may give up some of its surplus by paying for content delivery in order to obtain access to content delivery reports.

When the eyeball network deploys the caching infrastructure and charges the welfare-maximizing price for caching, then the network as a whole realizes the maximum value from caching (Fig. 4b). However, the eyeball network may have incentives to charge profit-maximizing prices, which creates a deadweight loss for the system. In this case, the profit-maximizing price is limited by two constraints. First, the eyeball network raises prices until the additional surplus it obtains is exactly offset by its share of the additional deadweight loss created from the price increase. Second, the prices charged for caching by the lowest cost transit network serves as an upper bound on the profit-maximizing price in the absence of eyeball network market power in negotiating termination charges [9].

Another way to realize the maximum value from caching for the network is for the eyeball network to pay the CDN an amount, equivalent to its bandwidth savings and increased revenue from improved end-user latency, to co-locate and terminate traffic. This has the effect of pushing down *MC* to the point where it overlaps with *MC′*. In this case, the CDN and the publisher appropriate all the benefits from caching (Fig. 4c). This will likely serve as a disincentive for the eyeball network to realize this deployment scenario.

In the presence of significant barriers to entry, a large eyeball network could still host a CDN and extract some of the CDN's profits through co-location and termination charges, as

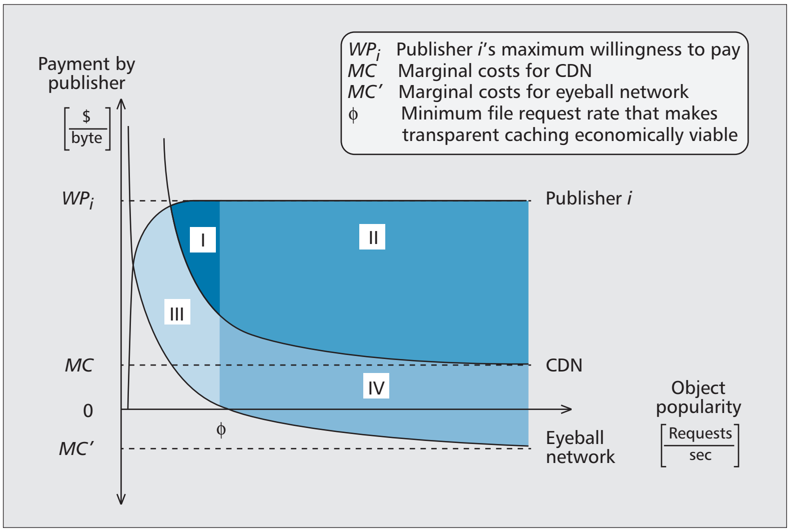

Figure 3. *Illustration of the viability of cache service provisioning for an eyeball network and a CDN. In the absence of monetary transfers between the publisher and the network, the eyeball network only caches objects in regions II and IV, whereas the CDN caches no objects at all. This suggests that payment transfers between publishers and network players will be necessary to incentivize networks to deploy sufficient caching infrastructure in an ICN architecture. Given a payment transfer mechanism, there are two ways to realize all potential benefits of caching (computed from regions I - IV). First, an eyeball network could deploy its own caching infrastructure. Alternatively, it could pay a CDN an amount equivalent to the bandwidth savings and increased end-user revenue it realizes from caches deployed by the CDN. The most desirable option for an eyeball network depends on the investment required, as well as, the appropriable benefits from owning caches.*

shown in Fig. 4d. This reflects a common deployment scenario in the current Internet. Although currently popular, we see from Fig. 4d that such a scenario leads to an inefficient result because of the deadweight loss. The deadweight loss comprises two parts. The first part results from the CDN paying to co-locate and terminate traffic within the eyeball network, whereas the second part arises because the eyeball network fails to pay the CDN to co-locate and terminate traffic. In practice, eyeball networks extract as much value as possible from the CDNs by raising the co-location and termination charges to the point where the additional deadweight loss created offsets the additional gain in surplus by the eyeball network or to the point where publishers gain greater surplus from using transit networks and choose them over CDNs.

The implications of the preceding analysis are clear. When a publisher's willingness to pay for caching services does not depend on the type of network that provides the service, then eyeball networks obtain significant appropriable benefits from deploying their own caches for commercial purposes and will likely do so in order to capture most of the benefits from caching. Despite the pricing advantage enjoyed by eyeball networks, publishers may take factors other than price into account when making their decision. For example, publishers may not want to buy caching from networks that provide competing content, even if such a network provides the lowest prices. Under such a scenario, our conclusion about the competitiveness of the eyeball network fails to hold.

[3] *See [10] for more details about surplus, social welfare and deadweight loss computations.*

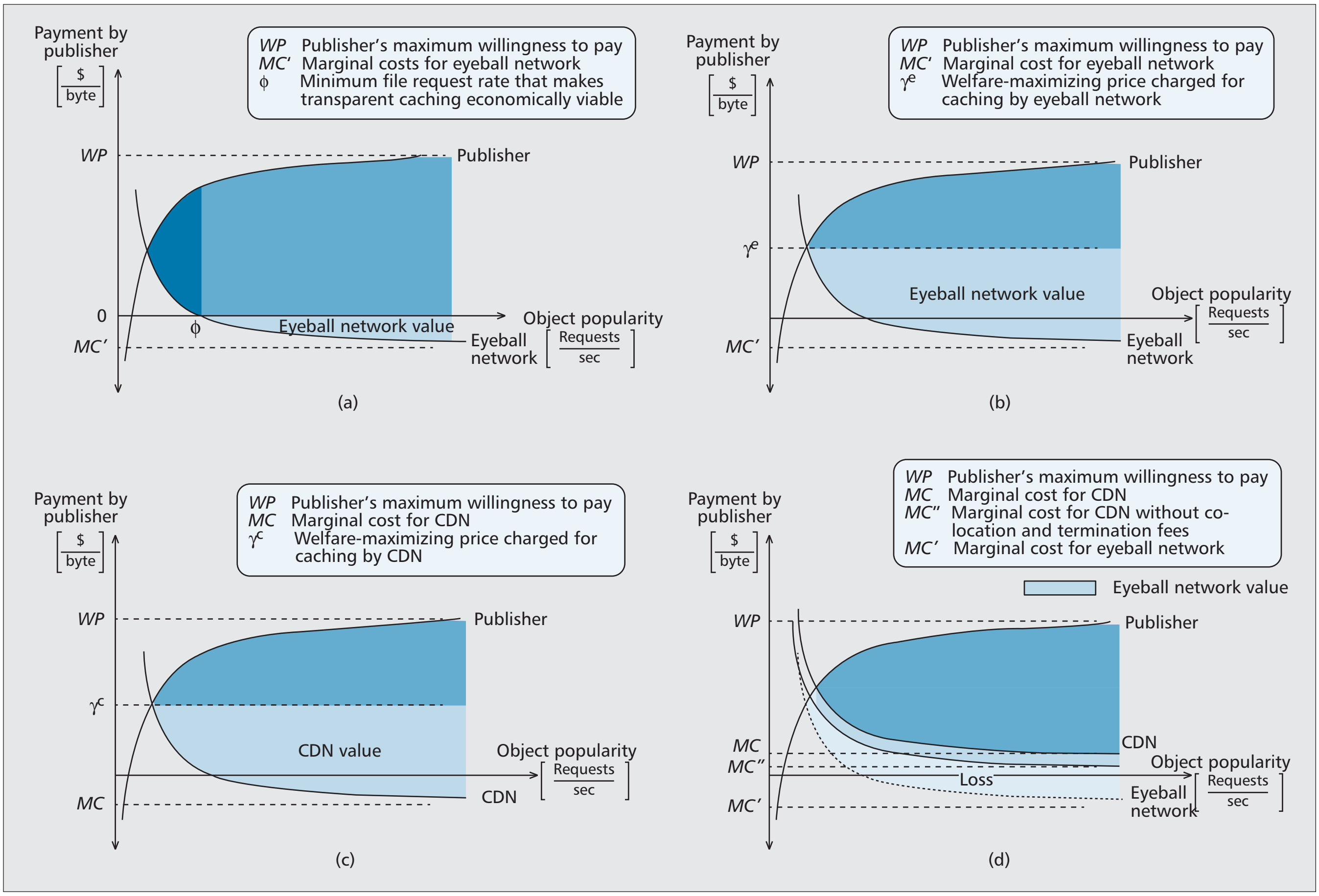

Figure 4. *Illustration of how network stakeholders appropriate caching benefits under various cache deployment scenarios. The eyeball network appropriates the most benefits when it deploys its own caching infrastructure: a) Eyeball network deploys transparent caches; b) eyeball network deploys commercial caches; c) eyeball network pays CDN to co-locate and terminate traffic; and d) CDN pays eyeball network to co-locate and terminate traffic.*

Even when publishers face significant transaction costs to establish relationships with eyeball networks or when eyeball networks face significant barriers to entry, it may still make sense for eyeball networks to deploy limited transparent caching within their networks. Future ICN architectures could support such scenarios by providing mechanisms for eyeball networks to easily identify files served close to it by other networks, in order to minimize duplication of efforts and the required investments.

Discussion

We showed that when transaction costs and barriers to entry are low, large eyeball networks have significant incentives to deploy caching infrastructure in order to appropriate the benefits from caching. Even when transaction costs for publishers are fairly high or when significant barriers to entry exist, eyeball networks still have incentives to deploy transparent caching for publishers with popular content served from distant servers. A logical question to ask is whether these results reflect the current situation and the extent to which they can be applied to a future ICN ecosystem.

The first observation we make is that, until recently, content delivery was dominated by third-party CDNs. This is mostly due to the low transaction costs that publishers incur when they do business with CDNs and the added value they obtain through aggregate content delivery reports across multiple eyeball networks. In addition, CDNs, such as Akamai, erected significant barriers to entry through patents on numerous caching and content delivery technologies. However, we see that large eyeball networks like AT&T have recently taken steps to eliminate the technological barriers through partnerships and acquisitions. As our model shows, large eyeball networks have significant incentives to deploy caching infrastructure when barriers to entry are low. This is a trend we currently see in the Internet and we expect it to continue in a future ICN architecture.

If eyeball networks could provide caching services through a single transaction broker, then publishers will incur low transaction costs to do business with them, which will increase the appropriable benefits from caching. One could imagine a content delivery federation of eyeball networks, which serves as a single point of contact for its constituent members. Alternatively, third-party CDNs could evolve into a business where they license their technology to multiple eyeball networks and act as a transaction broker for all eyeball networks that utilize their technology. We are beginning to see such trends in the market, with managed and licensed CDN offerings from major players, such as Limelight, Edgecast, and Akamai. Thus, ICN design must seek to facilitate such measures aimed at minimizing transaction costs across multiple eyeball networks.

In our model, we have assumed that other cache providers interconnect their caches deeply within the eyeball network. However, this does not reflect current reality. For instance, even with the presence of a CDN or a transit network that provides caching, eyeball networks may still find it desirable to deploy transparent caching to save the metropolitan bandwidth required to transport files across distant locations within their networks. This is especially true in small towns and rural areas, where the caches placed by a CDN may be very far away from some clients. For the same reasons, cellular operators may find it beneficial to locate transparent caches at cell towers in order to save on backhaul. Thus, it is entirely possible that multiple caches may be deployed by different network players to serve the same content to the same end-users in an ICN ecosystem. We leave the analysis of the competitive effects of such a scenario for future work.

Even though ICN could improve on security and content delivery, it also introduces a few issues that deserve consideration. For starters, caching and content delivery infrastructure provide networks with a means to circumvent transport-focused net neutrality regulations. For example, the net neutrality rules enacted by the Federal Communications Commission in the U.S. in 2010 focused solely on transport infrastructure. Hence, networks can, in principle, implement and monetize differential quality of service by leveraging their caching infrastructure. In particular, eyeball networks can favor particular content publishers through caching algorithms or the prices they charge for caching content. Furthermore, large eyeball networks can also influence the competitiveness of caching service providers and publishers by adjusting the prices they charge for co-location and traffic termination.

We end this section by pointing out that our analysis does not account for the fact that the actual bit delivery business forms a decreasing fraction of the revenues of CDNs. Many CDNs are increasingly moving into the business of providing value-added services, such as application delivery, real-time analytics, security, and consulting. For instance, value-added services now form more than half of Akamai's annual revenues. Given this shift, one could easily imagine a scenario where CDNs bundle actual bit delivery with other value-added services in order to remain competitive. Thus, the level of CDN cache deployment in an ICN ecosystem may be higher than our model suggests.

Lessons for ICN Architecture and Protocol Design

In this section we discuss the implications of our findings for the design of ICN architectures and protocols.

Accounting, Reporting and Payment Mechanisms

Our preceding analysis implies that without some form of payment flow, networks will fail to deploy sufficient caching infrastructure. Thus, ICN must incorporate features that make it easy to implement payment mechanisms to support caching-based business models. In order to be useful, these features should exhibit low transaction costs and provide a means for transparent verification.

For instance, ICN protocols should make it easy for publishers to indicate their willingness to partake in the caching market and the conditions under which they will participate. In addition, the protocols must enable networks to easily determine for each object whether to cache it based on identifiable and trustworthy information about the publisher of the object or its authorized intermediaries, and the quality of caching service the publisher is willing to pay for. These features will ideally provide networks with the capability to aggregate information about content delivered on behalf of publishers across multiple networks. Furthermore, the design of the architecture must seek to minimize the number of entities with whom a publisher must establish business relationships for caching services.

Moreover, payment mechanisms must provide disincentives for fraud. For example, network operators could have incentives to over-report the volume of content delivered in order to extract more revenue from publishers. Therefore, in the absence of effective mechanisms to verify content delivery, publishers may not have incentives to participate in the caching market for fear of potential fraud. Furthermore, ICN architectures must provide reporting mechanisms that enable publishers to obtain information about who accesses their content, when they access it, and how they access it. This kind of information is necessary for publishers to build models for targeted advertisement.

Cache Hit Ratios

Among the factors that directly affect the economic viability of caching, the cache hit ratio is perhaps the one that the design of ICN can directly influence. Since networks have more incentives to deploy caches when the cache hit ratio increases, ICN design must emphasize cache performance in addition to primary concerns, such as efficient transport and security.

Furthermore, mechanisms to enforce access controls should also take into account the impact on the cache hit ratio. For example, uniquely encrypting content for each user as part of digital rights management (DRM) greatly reduces the cache hit ratio, which makes caching unattractive. Thus, the trade-offs between cache hit ratios and access controls must be carefully studied in order to design ICN protocols that incentivize cache deployment. This problem is not unlike the problems encountered in secure multicast, since hierarchical caching can be viewed as a form of asynchronous multi-cast.

ICN must incorporate features that make it easy to implement payment mechanisms to support caching-based business models. In order to be useful, these features should exhibit low transaction costs and provide a means for transparent verification.

Content owners and ICN designers need to think of creative ways to balance the needs of access control and the performance of caches in order to improve the incentives for network players to deploy caches in an ICN ecosystem.

Conclusions and Policy Implications

In this article, we evaluated the economic incentives of different types of network players to partake in an information-centric network. We showed that the level of caching supplied with transparent caching is inefficient and results in a deadweight loss. In addition, we showed that publishers extract significant value from transparent caching. With a payment flow from publishers for content delivery, the level of caching supplied increases because cache providers extract some of the publisher surplus for themselves.

Moreover, we identified two deployment scenarios that maximize social welfare when a payment flow exists between the publisher and the caching service provider. In the first, eyeball networks provide the caching infrastructure through an entity that serves as a transaction broker between publishers and various networks. In the second, eyeball networks pay third-party content distribution networks (CDNs) an amount, equivalent to the realized bandwidth and transit savings from caching, to deploy caches. Even though both deployment scenarios maximize welfare, we showed that the latter deployment scenario is unlikely to be realized in practice because eyeball networks do not share in the value created. This explains the emergence of caching federations and CDNs evolving as brokers for eyeball network caching services. We also illustrated the nature of the deadweight loss that results when large eyeball networks use their terminating access monopoly to extract rents from other cache providers in the form of termination and co-location fees.

Additionally, our analysis suggested that ICN design must provide mechanisms to easily identify authorized intermediaries for files, in order to minimize duplication of efforts to provide caching infrastructure. For instance, an eyeball network can deploy a smaller transparent cache when it can identify files which are served by a nearby CDN. Moreover, we pointed out that while publishers may have legitimate rights to limit access to content using various means, it is important that the means employed do not negatively hamper cache hit ratios. For instance, per-user encryption based techniques for digital rights management (DRM) successfully achieve access control at the expense of cache hit ratio. Thus, content owners and ICN designers need to think of creative ways to balance the needs of access control and the performance of caches in order to improve the incentives for network players to deploy caches in an ICN ecosystem.

Finally, we pointed out that caching infrastructure provides one avenue for networks to circumvent transport-focused net-neutrality regulations. In particular, it is reasonable to expect networks to use caches as a strategic asset to open up new revenue streams from differential quality of service business models. For instance, networks can favor a publisher's content through the algorithms employed at the caches. Hence, policy measures taken to address net-neutrality must also take into account caching infrastructure. Additionally, we showed that large eyeball networks can implement differential pricing for interconnection and co-location, depending on the CDN and the CDN's customers. Therefore, regulators will need to address interconnection issues in an ICN-based architecture.

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