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ABSTRACT

Peer-to-Peer (P2P) networks have emerged as a popular alternative to traditional client-server architectures for the distribution of information goods. While there is a great deal of research on these networks in the computer science literature, until recently there has been little academic research considering the salient economic characteristics of these networks. In this paper, we outline some important economic characteristics of these networks. We show that while the characteristics of services provided over P2P networks are similar to public goods and club goods, they have many important differences and hence there is a need for new theoretical models as well as empirical and experimental analysis to understand user behavior. We then identify several important areas for study with regard to the economics of P2P networks and review recent academic papers in each area.

1. Contribution

Peer-to-Peer (P2P) networks have recently emerged as a popular medium for consumer-to-consumer resource sharing and hold promise as an architecture to facilitate knowledge management and collaboration within businesses. To date, most of the research on these networks has focused exclusively on their technical dimensions. However, an emerging literature integrates the technical dimensions of these networks with explicit consideration of their economic characteristics.

This paper contributes to IS research in several ways. First, we discuss prominent P2P architectures and applications. Second, we highlight several significant economic characteristics of these networks and compare these characteristics to similar characteristics in the economics literature. Third, we review the nascent literature integrating economics into the study of the performance and design of P2P networks with a focus on the recent 2003 Workshop on the Economics of Peer-to-Peer networks at the University of California at Berkeley. And fourth, we identify important areas for future research in this domain.

2. Introduction

P2P networks allow a distributed community of users to share resources in the form of information, digital content, storage space, or processing capacity. The novel aspect of these networks is that, in contrast to client-server networks where all network content is located in a central location, P2P resources are located in and provided by computers at the edge of the network (a.k.a. "peers").

It is interesting to note that while they are perceived to be a recent phenomenon, P2P networks have their origins in many of the early Internet applications and architectures. Internet Relay Chat (IRC), which was developed in the late 1980s, was one of the first P2P network services. IRC allowed for the transmission of text messages, and later digital content, directly between groups of network users. Likewise, the Domain Name System, and Usenet bulletin boards exhibit elements of P2P design. Thus, it can be argued that the P2P design concept is embedded in many of the original Internet protocols and applications (Minar and Hedlund 2001).

Still, the widespread popularization of P2P at the consumer level can be traced to the release of the Napster program in May 1999. Napster was developed in a matter of months by Shawn Fanning, then a Northeastern University student. Initially distributed to 30 friends, the program grew to 25 million users worldwide within its first 12 months of operation (Strahilevitz 2002).

Napster (along with OpenNap, an open source version of the Napster protocol) is an example of P2P networks with a centralized database of content (Asvanund et al 2003a). Users who logged into the Napster network upload a list of the content they are sharing to a mirrored set of central servers owned by Napster. Users who wanted to access content on the network would issue a query against this central database that would then point them to a list of peers who had the content. The searching peer would then download the file directly from the peer who provided the content. This architecture gave users a high degree of visibility to content on the network and thus improved the ease of user search. However, it also introduced a vulnerability to the network: The network ceased to function if the central servers were shutdown, as a judge ordered Napster to do following a lawsuit issued by the RIAA.

Many networks that have emerged following Napster's demise have adopted a decentralized or hybrid structure (Asvanund et al 2003a) to reduce both legal and technical risks from the loss of the central server and to reduce the monetary investment required to operate the network by distributing database management responsibilities to the individual peers. Gnutella 0.4, Gnutella 0.6, and Kazaa are notable examples of such networks.

The Gnutella 0.4 protocol features a distributed catalog of files. To connect to a network, a Gnutella peer would establish simultaneous connections to approximately 3 other peers on the network. These peers would also maintain simultaneous connections to other peers. In this mesh architecture peers maintain a list of their own files. A peer can issue a search to its neighbors with a time-to-live (TTL) definition (typically 7). This search will be forwarded through the network up to the number of times defined by the TTL field. If a peer that receives the search message has the requested content, they will send a reply back through the chain to the originating computer. The advantage of this architecture is that Gnutella 0.4 networks do not have a central point of vulnerability. However, this advantage comes at a cost of reduced visibility to network content.

The Gnutella 0.6 and Kazaa protocols adopt a hybrid architectural design. In each of these networks a small set of computers are selected to maintain local content databases. In Gnutella 0.6 these are called ultrapeers and in Kazaa they are called supernodes. In both cases peers on the network indicate their willingness to serve as local content databases and are selected for this task by the network protocol. Other peers connect directly to these ultrapeers and upload their list of content as in the Napster protocol. The ultrapeers are then interconnected in much the same way as peers on a Gnutella 0.4 network. Searches for content are first issued to the ultrapeer and then these queries propagate to other interconnected ultrapeers using the same TTL field discussed above. Thus, these networks have the advantage of increased content visibility and enable more efficient search. However, shutdown risks are minimized because new ultrapeers can be selected if some existing ultrapeers are disabled.

File sharing using these and similar networks has been called the "killer app" of P2P, and rightly so. The Yankee group estimates that consumers swapped over 5 billion music files over P2P networks in 2001 (Dignan 2002). A recent study by Ipsos-Reid finds that 23% of the American population over age the age of 12 has downloaded MP3s over the Internet.[1] This proportion is likely to be much higher among the critical 12-21 year-old demographic. In 2000, a Gartner study found that Napster accounted for up to 75% of the traffic on some university LANs (Shuchman 2000). More recently, the March 2002 shutdown of Morpheus resulted in a 50% drop in the number of packets sent on Carnegie Mellon's wireless network.[2]

However, while P2P file sharing networks are among the most popular applications of P2P technology, P2P technology is also gaining adoption in a variety of other arenas. For example, P2P has gained adoption for distributed computing (e.g., SETI@Home), enterprise knowledge sharing (e.g., Bad Blue), and user collaboration (e.g., Groove Networks). Further, while most of the previous examples of consumer P2P networks have a high proportion of copyrighted content, there is no reason that Digital Rights Management (DRM) cannot be incorporated into such P2P networks. For example, the subscription-based Napster service launched in early 2002 used DRM technology within its P2P architecture to protect copyright holders. Subsequently, Altnet has proposed a similar scheme as an overlay to the Kazaa network.

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[1] Source: http://www.ipsos-reid.com/media/dsp_displaypr_us.cfm?id_to_view=1414
[2] Conversation with Marvin Sirbu, April 2002.

A great deal of research has analyzed the technical features of these networks, particularly on improving the efficiency of P2P indexing schemes (e.g., Ratnasamy et al 2001, Stoica et al 2001), content caching schemes (e.g., Druschel and Rowstrown 2001, Bhattacharjee et al 2003), architectural designs (e.g., Kirk 2003, Sripanidkulchai et al 2001). Until recently little research has been conducted regarding the economic characteristics of P2P networks and how these economic characteristics might impact their design and operation. The remainder of this paper seeks to highlight this important area of P2P research and proceeds as follows. In section 2, we analyze the economic characteristics of peer-to-peer networks focusing on comparing the services offered over peer-to-peer networks to traditional private, public, and club goods. In section 3, we identify important areas of research integrating an economic perspective into the analysis of P2P networks and review selected recent papers in each area. In section 4, we conclude and discuss fruitful areas for future economic research relating to peer-to-peer networks.

3. Understanding the Economics of P2P Networks

While P2P networks vary in their architectural design, in all P2P networks files are transferred directly between the computers of users (a.k.a. peers) connected to the network. Further, once these files have been delivered, the user accessing the file, by default, becomes a provider of that content. Thus, in an ideal case the provision of content on the network will scale to match the level of demand for the content. To the extent this holds, P2P networks share some of the characteristics of public goods and club goods. Public goods have the characteristics of non-excludability in supply (individuals can't be excluded from consuming the product) and non-rivalry in demand (one individual's consumption does not diminish another user's value of the product) (Hardin 1968). Clean air is a typical example of a public good. Club goods are goods that are excludable in supply but non-rival in demand (Buchanan 1965).

P2P networks share many of the properties with the public or club goods, but they are different from both of them on many dimensions. In the ideal case, P2P networks will exhibit both non-excludability (information is made available to all members of the network) and non-rivalry (consumption by one user doesn't decrease network download possibilities in the absence of free-riding). However, in the presence of free-riding, P2P networks will exhibit levels of rivalry (Asvanund et al 2003a), which distinguishes them from either public goods or club goods. Thus, it may be possible to think of services provided by P2P networks as a new class of economic goods distinct from the existing private, public, and club good classes. For example, unlike other public goods, the provider of the good is also the consumer of the good. Hence on P2P networks, a user can be a provider, or consumer, or both. This has implications for the formation and sustainability of P2P networks as shown by Krishnan et al (2003).

An important observation from public goods literature that seems to extrapolate to P2P networks is the inability of individually rational behavior to bring about socially optimal outcomes. It is possible to model P2P users as economic actors who seek to maximize their private utility through their actions. It is well known in the public goods literature that in the absence of outside incentives the individually rational allocation of resources in such an environment will, in general, be less than the socially optimal outcome.

One example of this in the context of P2P networks is the prevalence of free-riding. The failure of each consumer to consider the benefits for others of her public good provision is known as the free-rider problem. Following Hardin (1968), people refer to it as "the tragedy of commons."

Two results from the public and club economics literature are significant in the context of P2P networks. First, Hardin (1968) argues that the self-interested consumption of public goods may deplete the overall public utility, a.k.a. the "tragedy of the commons." Second, the propensity to "free-ride" (enjoying the public good provided by others while not supplying the good yourself) worsens as group size increases as argued by Olson (1968) and shown analytically by Palfrey and Rosenthal (1984) Hindriks and Pancs (2001), and Dixit and Skeath (1999) among others. These results are based on pure self-interest. Including the possibility of altruism on the part of users increases the provision of public goods (Andreoni and Miller 2001). This is potentially a significant factor for P2P networks as many authors have observed that altruism plays a significant role in the provision of public goods (Ledyard 1993).

In P2P networks, free-riding could occur if users consumer network resources without providing resources to the network in the form of shared files. Thus, while most P2P clients enable sharing by default, users also usually have the option of disabling sharing. Users may choose to disable sharing because of legal concerns,[3] or because of the scarcity of networking or computing resources. Free-riding in this way allows users to utilize their resources (disk space, band-width, content) privately while consuming other users' resources.

Given the similarities between the services provided over P2P networks and public and club goods it is not surprising that empirical studies have found high degrees of free-riding in P2P networks. For example, Adar and Huberman (2000) surveyed the Gnutella 0.4 network in August 2000, and found that 70% of peers on the network did not provide songs and that the top 1% of sharing hosts return 50% of all responses. Similarly, Asvanund et al (2003b) report that 56% of Gnutella 0.6 peers did not share files in September 2002. These high levels of free-riding led

[3] For example, the FBI recently announced they would target individual P2P users who shared copyrighted files.

Adar and Huberman (2000) to observe that "free-riding leads to degradation of the system performance…if this trend continues copyright issues might become moot compared to the possible collapse of such systems."

Will the economic characteristics of resource provision on P2P networks lead to the ultimate collapse of such systems? Can user incentives by designed into such systems to forestall such a collapse? How can trust be enhanced among a set of distributed self-interested peers? What are the implications of P2P systems on the balance between the rights of copyright holders, network entrepreneurs, and users? We raise these and related areas for research in the next section. We also review selected recent papers in each area with a focus on selected papers presented at the 2003 Workshop on the Economics of P2P Networks at the University of California at Berkeley.[4]

4. Analyzing the Economics of P2P Networks

4.1. Incentives

One obvious question raised by the previous section is how will user behavior respond to the economic characteristics of P2P networks and how can network designers influence this behavior through incentive mechanisms. This question is particularly important in light of recent observations of the importance of incentive alignment for Information Technology design (Ba, Stallaert, and Whinston 2001). One obvious area where economic incentives find application in P2P networks is controlling free-riding behavior on the part of users.

As noted above, free-riding behavior occurs when a user consumes network resources without providing any resources — typically in the form of sharing content files — and this situation may deteriorate in larger P2P networks where social norms are likely to be weakened (Olson

[4] More information is available on this conference at the conference website: http://www.sims.berkeley.edu/research/conferences/p2pecon/

1968). A variety of solutions have been proposed to reduce the problem of free-riding on P2P networks. The most common proposal follows a pricing model, where incentive compatibility is achieved by pricing a scarce network resource (e.g., MacKie-Mason and Varian 1995 and Wang, Peha, and Sirbu 1996). In the spirit of pricing network resources, Golle Leyton-Brown, and Moronov (2001) propose to charge for the use of P2P network capacity through a system of micro-payments. Similarly, Chandan and Hogenborn (2001) analyze the use of micro-payments in the context of wireless P2P networks and find that micro-payments may be able to provide an incentive compatible solution to the free-riding problem.

However, it is also interesting to note that direct payments between peers may be impractical in many common P2P implementations. For example, it is difficult to imagine transfer payments between users of a knowledge sharing P2P network with an enterprise. Likewise, in many consumer P2P networks direct micro-payments will be difficult to implement because of the anonymous nature of network usage. In these settings it will be particularly important to develop non-priced incentives to encourage efficient behavior on the part of P2P users. Some examples of non-priced incentives could include delay times (e.g., providing priority queuing to users to share more content with the network), network membership (e.g., threatening to remove non-sharing members from the network), or peer ratings of content providers. Krishnan et al (2003) provide an example of such an approach. Strikingly, their model finds that it may not be socially optimal for all users to share depending on the cost an individual user incurs when sharing and the value that their sharing would provide to the remainder of the peers on the network. They use quality-of-service as a tuning parameter to induce the optimal amount of sharing.

Several authors have proposed similar non-priced mechanisms for sharing based on implicit or explicit reciprocity among users. For example Vishnumurthy et al (2003) propose KARMA, a system for tracking both user's contribution to and consumption of network resources. Each user receives a particular "karma" score, increasing in contribution and decreasing in consumption of network resources, which governs their future consumption of network resources. Similarly, Kamvar et al (2003) propose a similar scheme based on the possibility that self-interested peers will not forward query requests from other peers. In their network, peers "buy and sell" the right to respond to queries from other network users. Ranganathan et al (2003) argue that sharing in P2P network is akin to Prisoner's Dilemma problem such that non-sharing is the only dominant outcome. They then argue that if the game is extended to multi person with explicit mechanisms like reputation-based *Peer-Approved* and *Service-Quality*, and the *Token-Exchange* pricing scheme then it improves the level of sharing in the network. In both these mechanisms, higher reputation leads to better quality of service, which in turn encourages sharing.

4.2. User Behavior and Motivation

A closely related area of inquiry concerns what motivates users to share on P2P networks. Is it individually rational behavior? Altruism? Some combination of the two? The analysis of user behavior is a fruitful area of research, particularly given the importance of incentive design for efficient network design.

Several recent papers seek to understand and explain user motivations when contributing to P2P networks.

Gu and Jarvenpaa (2003) provide an empirical study on sharing behavior on users on P2P technical support forums. They argue that many times users tend to share because of altruistic reasons or "warm glow" effect as they call it. Feldman et al (2003) on the other hand argues that sharing does not impose as much cost as users think in a broadband symmetric network. But in other cases when upload and download speeds are different (like ADSL), sharing can lead to substantial latency. They also show that prioritizing the TCP traffic could potentially lead to better network performance in some cases. Finally, Strahilevitz (2002) argues that sharing occurs in network due to "charismatic code" — the intentional perception given to network users that sharing is a common and normal practice in the network.

4.3. Reputation and Trust

The development of systems to track the reliability or consistency of a peer's contribution to other members of the network is also closely related to the development of incentive systems for P2P networks. Such systems build on the incentives schemes mentioned above which track a user's contribution in the present period (e.g., Krishnan et al 2003), by tracking a user's contribution over a longer time period.

P2P reputation systems are closely related to the efforts of online communities, such as eBay, to develop incentive-compatible systems for rating the performance of a distributed set of users (see Dellarocas 2003 for a review of this literature). However, the design of reputation systems for P2P networks is complicated by two factors. First, the distributed and intermediated nature of P2P network interactions makes it easy for users to conceal or change their identity. Second, in many some fully distributed applications, the administration of the rating system must also be distributed throughout the network, making it vulnerable to coordinated gaming strategies. Dutta et al (2003) and Shneidman and Parkes (2003) discuss in more detail the difficulties associated with fully distributed reputation networks.

With regard to such systems, Lai et al (2003) study the evolutionary prisoner's dilemma (EPD). Since EPD characterizes cooperation that requires *repetition* and *reputation*, it needs to be modified in the context of P2P networks because of the lack of repeat interaction amongst the peers and easy acquisition of pseudonyms. They introduce the concept of "private" history and “shared” history as a way to encourage sharing. Shared history is a centralized pool where peers’ past behavior is noted and services are provided according to their reputation.

Other work in this domain includes Moreton and Twigg (2003) who compare the reputation mechanism with the payment mechanism and then argue that “stamp trading” protocol which is more general in its application, captures the essence of both mechanisms quite well. Cohen (2003) on the other hand argues that a “tit for tat” treatment leads to a significant improvement and robustness in a P2P network. He demonstrates the practical implementation of this mechanism in the context of the BitTorrent P2P network. Kung and Wu (2003) combine elements of incentive design with persistent trust ratings by proposing an admission control system that provides quality of service differentiation to users based on a distributed mechanism that tracks user reputations. Woodard and Parkes (2003) employ mechanism design techniques in the context of network formation. They analyze how a network of distributed, self-interested peers might be able to form.

Reputation and trust mechanisms can also help to protect against a coordinated attack by an outside adversary. For example, the Recording Industry Association of America (RIAA) and its member organization have recently initiated several attacks against P2P networks by flooding the network with “fake” files labeled to appear as though it were real content (the economics of this strategy is discussed in more detail below). Such an attack is facilitated in a distributed network because it is difficult to tell whether an individual offering a file is a genuine sharer or an adversary posing as a legitimate sharer. Rosenthal et al (2003) discuss mechanisms to protect against coordinated attack in the context of protecting information goods for library services.

4.4. Intellectual Property

The strategy of the RIAA is motivated by their legitimate desire to protect their intellectual property from unauthorized sharing. However, this legitimate effort to protect intellectual property can, in some cases, collide with the interests and rights of entrepreneurs attempting to develop novel information sharing networks, individuals exercising fair use rights associated with legitimately purchased materials, and network operators seeking to protect the privacy of their users.

Thus, the issue of liability, privacy and intellectual property rights on these networks is thus a promising area of research that has academic, policy as well as commercial implications. From an academic perspective, a natural question is: how much of an impact do P2P networks have on sales of associated information goods? Liebowitz (2001) argued that early data suggested that the impact of P2P networks on record industry sales was minimal. Png and Hui (2002) have a similar finding, arguing that P2P networks had significant promotional value for record companies, which militated against losses. However, using more recent data, Liebowitz (2003) finds that the impact may be a significant cause of the recent downturn in record sales.

From a policy perspective, how should the interests of artists and copyright creators be balanced against the interests of network users and entrepreneurs designing new distribution mechanisms for information goods? From the perspective of commercial industries, is it possible to use P2P networks as a promotional channel while simultaneously reducing commercial risk from piracy as argued by Png and Hui (2002) and what form would such a network take?

Another interesting commercial question concerns the optimal response of copyright holders to the threat of piracy. Recently, Varian (2003) studies the social cost of sharing and shows that when sharing is possible and a monopolist can observe it then generally it can price the product such that it leads to an inefficient outcome and low overall welfare.

It is also possible to consider legal and strategic options available to copyright holders to make participation in P2P network less attractive for users. In a typical scenario, a user's net utility from consuming a product is $U - p - sc$ where U is the utility of the product, p is the price of the product, and sc is the search cost associated with obtaining the product. In the case of MP3 file sharing for a record company's file sharing site to yield higher utility to a potential customer than using a copyright-infringing site the record company would need $U_r - p_r - sc_r > U_p - sc_p$ where the price to use the copyright-infringing site is assumed to be 0. What is interesting for the record companies is that, unlike in a typical situation where they can only control their own utility, price, and search cost, in the case of MP3 file sharing networks they can also influence the utility and search cost of the competing network. Copyright holders can influence the utility of content downloaded over copyright-infringing sites by flooding the network with fake files and thereby increasing user's search costs for their desired content (see Segal 2002 for example). In such a scenario, the record company would register numerous peers on the copyright-infringing site each with a set of MP3s that use the same naming structure as popular music content, but which contain no usable content.[5] The end result should be to increase the number of files a user must download before they find the "real" content they were looking for. By lowering the utility and increasing the search costs of their competitors' file sharing networks, the record company's web sites will have more flexibility in setting the utility level of their content (e.g., by restricting the legal uses of the files) and their prices. Copyright holders can also threaten users with fines or lawsuits for illegally sharing and downloading copyrighted content. This raises the implicit cost

[5] The companies MediaDefender and Vidius both advertise software product to make this process easier for the record companies.

of users to share content, thereby increasing free-riding, and thus reducing network performance and scalability (Asvanund et al 2003a). This strategy may have been responsible for a 15% drop in week-to-week file-sharing traffic for the week ending July 6, 2003.[6]

Another interesting commercial question concerns the interests of Internet service providers who provide benefit to their users through the provision of P2P network services, but who also incur significant costs through the consumption of scarce bandwidth by P2P traffic. Many colleges and universities have found that P2P traffic makes up more than 50% of traffic on their links to the Internet. Similarly, a report by Sandvine.com found that P2P packets made up 60% of the traffic on major Internet backbone connections. These problems are exacerbated by the fact that connections in many popular P2P networks are not optimized for either similarity in user interests or similarity in user locations with respect to the network topology. This can result in large transit fees being borne by the ISP seeking to provide access to P2P applications. A natural response to these high bandwidth requirements, and one adopted by several Universities, is to limit the quality of service provided to P2P packets passing through the organization's link to the Internet with the intention of getting users to limit their use of P2P. A more draconian approach is to shutdown P2P network users. However, some alternate approaches are emerging. For example, Asvanund et al (2003b) propose economic models to encourage the dynamic formation of clubs in P2P networks based on common interests, similar provision of resources, and proximity with regard to network location. Similarly, Singh et al (2003) propose conditions under which internet service providers would benefit from sponsoring their own ultrapeers for the provision of P2P network resources.

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[6] "Traffic to filesharing sites drops" Cnn.com, http://www.cnn.com/2003/TECH/internet/07/14/filesharing.drop.reut/index.html, July 14, 2003.

5. Discussion

It is quite evident from the growth of P2P networks in last 2-3 years that they are becoming popular tool for content sharing and distribution. While the popularity of these networks has been mainly from consumer P2P networks, many enterprises have been using these networks for as knowledge management tools to share information across the enterprise.

A review of the recent literature on P2P networks suggests that while the technical developments have kept pace with the growth of these networks, economic and social analysis of these networks is still in a nascent stage. Understanding P2P network operation from the perspective of the economic characteristics of content provision and user behavior will be critical to developing protocols and systems to ensure the efficient operation of these networks.

Public and club goods provide a useful starting point for the economic analysis of P2P networks. P2P networks share many characteristics with public and club goods, but differ from these goods in important ways. Since the literature on public goods is quite extensive, it allows the researchers to extrapolate some of the results from this literature. But we note that not all results are equally applicable. Since these goods are essentially a different class of product, we need to understand the mechanism of these networks carefully before applying these results. In many cases, we need different models to understand user behavior.

Another important observation we have noted is the existence of extensive free-riding on these networks and its social and economic implication. Free-riding may significantly reduce the performance of P2P networks. Besides the economic literature, group behavior and social network literature sheds some light on free-riding on these networks. It is believed that larger groups lead to more free-riding. But at the same time, altruism could mitigate these effects quite significantly. As these networks continue to grow, we need new theoretical models as well as experimental and empirical data to understand user behavior on these networks.

An emerging body of research seeks to integrate economics into the study of P2P networks. Significant questions addressed in this research include the role of incentives in improving network performance, the motivations of users who consume and provide resources in P2P networks, the application of trust and recommendation mechanisms to the unique environments present in P2P networks, and the balance between the rights of copyright holders, entrepreneurs, and consumers. However, significant open question remain in these and other areas of inquiry and it will be important for future researcher to pursue these questions in the coming years.

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