A case for holistic incentive design

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Introduction

As distributed systems that span multiple administrative domains proliferate, robust protocols increasingly need to incorporate the incentives of multiple stakeholders into their design. A significant challenge in designing incentive aware systems is layering: where are incentives required? who are the principals?

Peer-to-peer systems (P2P) push these challenges to the limit. Users are transitory, act independently, and strategize to maximize unknown utility functions. Moreover, users themselves are not the only players; ISPs and IT administrators impose limits on bandwidth hungry services. Content providers actively police P2P networks for copyrighted material, often introducing polluted files that merit system-level countermeasures [6].

In this paper, we argue for a holistic approach to incentive design in a P2P environment. P2P systems offer a rich base for experimentation regarding incentives. Their users act as a set of "fruit flies" for incentives research; their willingness to jump from service to service has resulted in the evolution of a diverse set of P2P protocols, implementations, and research insights. In this context, a holistic incentive design is one which is both *complete* and *self-contained*. By complete, we refer to addressing the challenges of operating on end hosts, e.g. rapid churn, potential for Sybil attacks, etc. By self-contained, we mean that all primitives required by the system are provided by the system, e.g. no out-of-band authentication mechanisms.

In the remainder of this paper, we expand on the notion of holistic incentive design, exploring a common set of issues that future P2P incentive strategies should take into account. We argue that existing work on incentive design has been crucial in bringing the community to a turning point; lessons learned can now be synthesized into a common set of holistic design criteria for incentive aware distributed systems.

The reality of churn

Many P2P designs make an operational distinction between behavior during periods of stability and periods of churn. Generally, static membership makes the analysis of performance, consistency, and overhead much more straightforward. Particularly in structured overlays, node arrivals and departures are often treated as a special state from which to adjust or recover. Although formal methods and provable guarantees are essential for reasoning about the fundamental properties of these systems, we argue that the separate consideration of behavior when stable and behavior when responding to churn is a significant hurdle that needs to be overcome before many analytical results can be applied to deployed systems, which tend to be perpetually responding to churn.

A concrete example is provided by BitTorrent. BitTorrent employs a tit-for-tat strategy to pair bandwidth matched peers. In the absence of churn, this matching is nearly exact, limiting the performance benefit of strategizing over peer selection. However, for live Internet swarms, rapid churn enables strategic clients to subvert BitTorrent's intended contribution incentive [4].

Robustness of incentive strategies should be studied under realistic churn characteristics. Fortunately, experimental studies have emerged that provide trace data characterizing churn in the wild [3, 2, 4]. This characterization can be used to parameterize models of user behavior in P2P systems. At the very least, it provides strong evidence that churn merits consideration in holistic incentive design.

Choice and the long tail

P2P protocol designs and incentive strategies both appeal to the capacity for choice among peers. Protocols rely on choice to provide the robustness associated with path diversity and wide replication. Incentive strategies leverage choice to prioritize the requests of comparatively good clients and discourage bad behavior by either reducing or terminating service. On the whole, P2P protocols and incentive strategies alike benefit from a large pool of users providing choices.

Unfortunately, measured P2P workloads suggest that choices are not always available. Object popularity in Kazaa is skewed [2], as is swarm popularity in BitTorrent [3]. For Kazaa, having only a few replicas degrades performance. The problem is worse still for BitTorrent; small swarms render its tit-for-tat incentive strategy largely inoperable [5].

Choice in P2P systems is often linked to the granularity of distribution. Most often, users are organized on a per-object basis, i.e. downloading one particular file or watching one particular live video stream. This organization is incompatible with the "long tail" observation that significant demand for content tends to come from the aggregation of requests for objects in the unpopular tail of the popularity distribution [1]. For these objects,

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choice is limited. Coping with limited choice requires techniques that allow users to find more sources of data as well as incentive strategies that provide a reason for those additional sources to contribute, i.e., incentives beyond the granularity of a single object.

In-band bootstrapping

In a P2P system, bootstrapping has multiple meanings. For some systems, it refers to finding the first peer through which a new user will learn about others in the system, as in Gnutella. For others, it refers to contacting a centralized coordinator to find peers or establish identity, as in Napster. In the context of incentive strategies, bootstrapping generally refers to the "seed money" given to new users. In some systems, this is explicit virtual currency. In others, it corresponds to a donation of initial data to trade, bootstrapping a reputation.

A common problem arising from bootstrapping incentive strategies in P2P systems is the well-known Sybil attack. If identities can be created freely and have value, users can game the system by simply assuming multiple identities. To combat this problem, many designs assume bootstrapping can be performed out-of-band by a centralized or trusted third party. In some cases, this is limited to assuming strong identities, e.g. keys from a PKI.

Although centralization or an identity management infrastructure can convincingly compartmentalize the bootstrapping problem, such solutions have proven difficult to make work in practice. Instead of engineering a secure method of providing new identities with value, we suggest that new identities be given no value whatsoever. Modern P2P system designs often include control plane management tasks such as tree maintenance or DHT routing. New users might bootstrap their standing with the system by contributing resources to these tasks. Crucially, these contributions can be made without first obtaining more valuable content data, a property that enables the Sybil attack. This style of bootstrapping requires expanding the scope of incentive strategies to cover both control and data planes, a holistic approach.

Incentives across services

Incentive strategies tend to be application specific—with good reason. Reasoning about users' utility functions alone seems to require application specific knowledge, and application specific workload characteristics restrict the design space (e.g., churn). Many designs assume that an incentive strategy needs to be tightly coupled with an application to work well. However, there are significant benefits to be realized from a generic incentives *layer* that transcends individual applications. Such a common layer would facilitate greater resource liquidity that could, for instance, afford a user improved download performance for a large file due to resources contributed in the past to participants in a video stream.

These goals suggest deployment of currency (or global reputation) and management of a digital economy. However, realizing this functionality without centralization while coping with problems like currency manipulation, inflation, and other standard economic challenges has proven difficult both in theory and in practice. Rather than attempt to provide the exact accounting and complete security of digital cash, we propose exploring design alternatives that relax the typical requirements of currency, such as centralization, while retaining sufficient liquidity to foster cross-service resource sharing. Centralized currency may not be required. For many P2P services, the scarce resource is bandwidth, e.g. file transfer, streaming video. For these applications, incentives based on bandwidth exchange can simplify reasoning about cross-service incentives as no exchange rate is required.

Conclusion

P2P systems are built on the resources of their users. Recently, the technical challenge of coordinating those resources has been matched by the difficulty of providing robust contribution incentives for them. This paper argues for a holistic approach to incentive design, one which minimizes external dependencies while taking into account known workload characteristics and the incentives of all participants.

We are currently developing a system at the University of Washington, called OneSwarm, that adopts this approach [5]. OneSwarm provides a generic data distribution layer with incentives designed to persistent across time, location, data, and service, implementing many of the design suggestions advocated here. However, OneSwarm represents just one point in the exploration of designing holistic incentive strategies. We look forward to future work that expands understanding of these issues.

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