Improving Efficiency and Fairness in P2P Systems with Effort-Based Incentives

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***Abstract*—[1] Most P2P systems that have any kind of incentive mechanism reward peers' contribution in terms of uploaded volume. Due to the disparity in bandwidth capacity between P2P users on the Internet, the common effect of such mechanisms is that the fastest peers reap the highest benefits. We take a different approach and study how to incentivize cooperation in P2P systems based on peers' effort, i.e., contribution relative to capacity. We make the following contributions: 1) we propose that volume-based incentive schemes in P2P systems unnecessarily punish slow peers and decrease overall system performance; 2) we advocate that principles from an alternate economic vision, Participatory Economics (Parecon), can inspire systems which are fair and ensure maximization of the social welfare, while being efficient at the same time and 3) we present simulation results of applied principles from Parecon to two popular real life systems: a) the popular file sharing BitTorrent protocol, b) a generic credit based sharing ratio enforcement scheme. Our approach yields higher system performance and fairness for both, and offers interesting new insights into P2P incentive design.**

I. Introduction

In this paper, our hope is to inspire new ways of looking at problems of incentives and social welfare in P2P networks. We argue that traditional methods of incentivizing and rewarding peers lead to the welfare of the fast peers while punishing honest, slow peers. For the first time in this field, to our knowledge, we apply principles of Participatory Economics (*Parecon*) to P2P systems. Parecon is an alternative economic vision in which reward is based on effort instead of volume of contribution, hence taking capacity into account. We argue that these principles can be adopted to design systems that are efficient while being fair and that support high social welfare [1].

There are various ways in which 'fairness' has been defined in the literature. However, the definition which encapsulates how the term has generally been used in P2P design is as follows: A P2P system is deemed fair if those peers who contribute more, receive a better service than those who contribute less [5], [8]. In view of the *Parecon* principle of rewarding *effort as opposed to size of the contribution or output*, we suggest that a system will be fair if those peers that make more effort and sacrifice, receive a better service than those who make less effort and sacrifice. Thus, while being incentive compatible, it gives both slow and fast peers in the system an equal level playing field. All peers, regardless of their bandwidth, *can potentially* make the same level of effort and sacrifice. On the other hand, slow peers simply can not compete with fast peers in terms of output or contribution levels.

Hence, we argue that those systems are fair that reward effort as opposed to output and hence are equitable to the less resourceful peers. We believe this is a better definition of fairness; one that gives equal opportunity to both slow and fast peers to be rewarded. On a similar note, we define 'social welfare' as the achievement of efficiency (i.e., *performance* in P2P systems) under equitable and fair arrangements.

What constitutes effort in a P2P community? We know that we want peers to contribute their resources to the network. Resources could encompass content, time spent sharing content, and the rate at which it is contributed. We would like people to share content for long periods of time at as high rates *as they possibly can*. So, their *relative* contribution is a good approximation of the effort they make for the welfare of the community. Possibly, effort such as sharing rare content, taking the time to rate content, and helping other peers communicate through NATs and firewalls, can also be taken into account.

In this paper, we first analyze in Section II how the notions of efficiency, fairness, social welfare, and incentives, have been utilized in the literature and implicitly in P2P systems. We suggest that broadening the scope of these terms would lead to systems that maximize social welfare as opposed to welfare of the few. We argue that designers of real life systems should be cognizant of their user base and should design systems where less resourceful peers, who can often constitute the majority of peers in the system, are not unnecessarily punished. Then, in Section III, we present a range of experiments in which we apply the principle of reward according to effort to the highly popular *BitTorrent* file sharing protocol. We show that not only our adaptation leads to more fairness, but even to a higher average system performance. Specifically, in the presence of a high proportion of fast peers, we observed the download speed of slow peers increases up to 63% at only a marginal loss for fast peers, of a 4% decrease in speed. Also, in the unmodified BitTorrent protocol, fast peers can achieve as much as 60% more speeds than slow peers whereas with our policy, the speeds of the two groups, converge to almost identical values, with fast peers reaching speeds only 2% more than slow peers.

Furthermore, in Section IV, we apply effort-based reward to

[1]The research leading to this contribution has received funding from the European Community's Seventh Framework Programme in the P2P-Next project under grant agreement no 216217 and the QLectives project.

a generalized credit based sharing ratio enforcement scheme, and show how it positively affects performance and fairness. Overall, we present an alternative approach that inspires the design of incentive mechanisms for P2P systems which are better suited to the heterogeneous nature of the Internet and its users.

II. Efficiency, Fairness and Incentives

What do system designers want from P2P systems? What kind of economic incentives do we desire? What are the values that underlie any economic system that we propose and how do we want to affect the behavior of peers using the system? Usually, a combination of the following goals has been sought.

- *More cooperation and less selfishness*
- *More efficiency and less wastefulness*
- *More equity and less unfairness*

We shall next consider each of the desired goals in turn.

A. More Cooperation and Less Selfishness

Fostering cooperation and eliminating selfishness is the primary goal of all incentive-based systems in P2P. We want peers to contribute their resources to the network. Resources could encompass content, time spent sharing content, and the rate at which it is contributed.

B. More Efficiency and Less Wastefulness

What do we mean by more efficiency? Normally Pareto optimality has been employed by P2P designers to measure efficiency. The first paper on BitTorrent, highlights the achievement of obtaining Pareto efficiency [3]. It is worthwhile to study what exactly Pareto optimality is and what it entails.

1) Pareto Optimality: A change from one allocation to another that can make at least one individual better off without making any other individual worse off is called a Pareto improvement. An allocation is Pareto efficient or Pareto optimal when no further Pareto improvements can be made [11]. Pareto optimality is not necessarily fair [12]. For example, allocating all resources to one individual and giving nothing to the rest is also a Pareto Optimal solution.

What is striking is that if P2P designers were to adhere strictly to Pareto optimality, then they would not have much, if anything, left to propose. This is because most solutions make *some* people better off and *some* people worse off. This has implications for designers working on improving existing protocols. It should be remembered that most recommendations for changes in policies, such as modifying BitTorrent's unchoke policy, are not Pareto improvements since they make some people worse off.

Mainstream economists try to circumvent this problem by using an extended concept of efficiency called the *efficiency criterion*. Succinctly, the efficiency criterion posits that if the overall benefits to any and all people of doing something outweigh the overall costs to any and all people, it is efficient to do it, and vice versa. As in mainstream economics, in P2P as well, social welfare has been equated with efficient outcomes [2], [4], [9]. Next, we shall discuss why this equation of social welfare with efficiency is inadequate.

2) Social Welfare: How can it be decided that the overall benefits to some people outweigh the costs to some other people? In the context of P2P file sharing networks, who is to say that it is efficient to provide reduced download times to faster peers while increasing the download times of slow peers? Fact of the matter is that *value judgements* are implicit in the efficiency criterion. A designer has to make value judgements on what she/he feels is a better solution. One designer might decide that increasing the utility of individual peers is of foremost importance while another designer might decide that the chief aim should be to increase the average system performance.

The point is that the principles and values we follow dictate how we formulate an answer to such questions. Based on personal judgement, a designer has to attach weights to the well-being of different peers.

We desire efficient outcomes, but such that they are fair and equitable to the less resourceful peers in the system. We therefore argue that the stated goal of numerous incentive works in P2P (e.g., in [4]: "achieving efficient outcomes for social welfare"), is inadequate unless qualified by the condition of equity. This brings us to our proposed values that determine how we reward peers in a system and how we can engender fairness and equity in the system.

C. More Equity and Less Unfairness

It should be straightforward to accept that there is disparity in Internet bandwidth among different P2P users. Peers that are slow will naturally get slower service as compared to the fast peers. However, it is up to P2P designers to ensure that the incentive mechanisms that we devise do not further punish slower peers.

It could be argued that it is fair that the fast peers, who contribute more to the system in terms of volume, overall get better service and more rewards from the system. However, we think that this is only fair if the sole maxims of remuneration available to us were the ones that rewarded peers for their fast connections. There are two familiar maxims of remuneration [7]:

a) *Payment according to value of one's personal contribution and contribution of the productive property one owns.* Peers should get out of the economy what they and their productive property (reputation or virtual money in case of P2P) contribute to the economy. b) *Payment according to the value of one's personal contribution only.* Peers should get out of the economy how much they contribute to the economy. This is in fact how people are currently remunerated in P2P settings. The faster connection a peer has, the faster it will be able to download (BitTorrent) and the more currency or reputation it will be able to earn in monetary or reputation based schemes.

it is clear that maxims *a)* and *b)* favor the faster peers who will be rewarded higher in a system that utilized either of these two maxims.

We now consider an economic system that utilizes a novel, third, maxim of remuneration, which in our view can facilitate

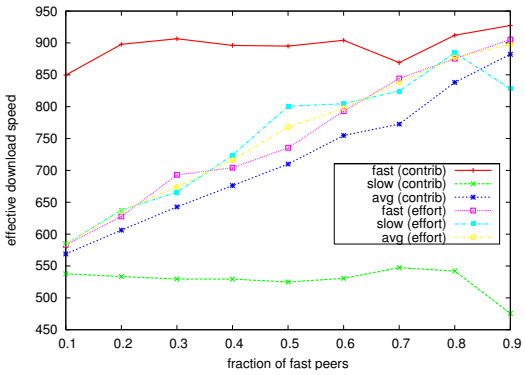

Fig. 1. The download speed of both fast and slow peers in networks with various fractions of fast peers, for the contribution-based policy (contrib) and the effort-based policy (effort).

the achievement of efficiency with equity.

D. Participatory Economics

Participatory Economics (*Parecon*) is an alternate economic vision developed by Michael Albert and Robin Hahnel [1]. A comprehensive overview of *Parecon* is available at [10]. For the purposes of this study, we shall concentrate on the *Parecon* principle of remuneration:

Payment according to effort and sacrifice. This maxim suggests that people should be rewarded for the efforts and sacrifice that they put into their work, rather than being paid for their output.

We believe that for P2P systems, this is a better option because it ensures that hard working peers who do their best to contribute to the system are rewarded even though they might not be well endowed in terms of bandwidth.

III. Efficiency and Fairness in BitTorrent-like Systems

In order to assess the efficiency and fairness of effort-based incentive schemes in practice, we performed extensive simulations using the highly popular BitTorrent protocol. We simulated systems using both the original BitTorrent policy (contrib) and our Parecon policy (effort). We used a BitTorrent simulator that accurately mimics the behavior of BitTorrent at the level of individual piece transfers, based on BitTorrent's *unchoke policy* and *rarest-first piece selection* [3]. In the original BitTorrent policy, peers reciprocate according to the received volume of contribution from others; in the Parecon policy peers reciprocate according to the effort another peer is giving, defined as the bandwidth it is giving relative to its upload capacity. To be more precise, a peer i periodically decides to whom it will allocate its (limited) upload slots by ranking the other peers according to values r_j where for a peer j it holds that: (i) $r_j = b_{ji}$ in the contrib policy; (ii) $r_j = b_{ji}/U_j$ in the effort policy. Here b_{ji} is the amount of bytes uploaded by peer j to peer i in some sliding window of time, and U_j the upload capacity of this peer.[2] In addition, in the BitTorrent protocol a peer periodically allocates a slot to a random peer, which we left unchanged.

We simulated systems with two classes of peers: fast peers with an upload capacity of 1024 KBps and slow peers with an upload capacity of 512 KBps. This polarized view allows us to clearly analyze the effect of a peer's capacity on its performance. We make the common assumption that the download bandwidth is not a bottleneck. In Fig. (1), the download speed of both classes of peers (averaged over all peers in that class) is displayed for systems with various fractions of fast peers. To our surprise, we observed that under all configurations the average download speed under the effort-based policy is *higher* than under the contribution-based policy. The effort-based policy is not only more fair, but also leads to an overall faster distribution of content, thereby dismissing classical claims that contribution-based reciprocation is necessary to optimize overall system performance. As expected, effort-based reciprocation is much more fair: compared to the polarized speeds observed with the contribution-based policy, the effort-based policy treats slow and fast peers much more evenly. When there are only a few fast peers, these few have to sacrifice a lot in the effort-based scheme against a meager improvement for the slow peers; when there are many fast peers, each has to sacrifice only little while there is a huge improvement for the slow peers. The various plots in Fig. (2) show the properties of both policies in more detail for a system with 50% fast peers and 50% slow peers. The effort-based policy leads to higher upload utilization, shorter download times, and a smaller variation in finishing times of slow peers. The first two points substantiate the claim that the effort based policy leads to a more efficient system with greater utilization of available resources and increased overall system performance while the last point demonstrates the fairness of the policy.

Hence, overall these experiments show that an effort-based policy in BitTorrent is advantageous regarding both system efficiency and fairness. The only subjective disadvantage is that the fastest peers have to 'sacrifice' some of their performance to the benefit of others, which we would argue is a very reasonable property of P2P systems both from a designer and user point of view[3].

IV. Efficiency and Fairness in Credit Based Enforcement Schemes

In order to establish that our approach can be applied to a variety of systems, we applied an effort based incentive policy to a simplified version of a credit based sharing ratio enforcement scheme. Sharing ratio enforcement schemes are used by most private BitTorrent sites, called trackers, in order to incentivize sharing (seeding) by peers. In such schemes, a peer is only allowed to download as much as it uploads.

[2]Determining the bandwidth capacity of a peer is a challenging task. However, a recent work presents a system for evaluating the bandwidth of nodes in a P2P network, in a secure way, that is efficient and accurate [13].

[3]This can be compared to redistribution mechanisms to promote social welfare in human societies.

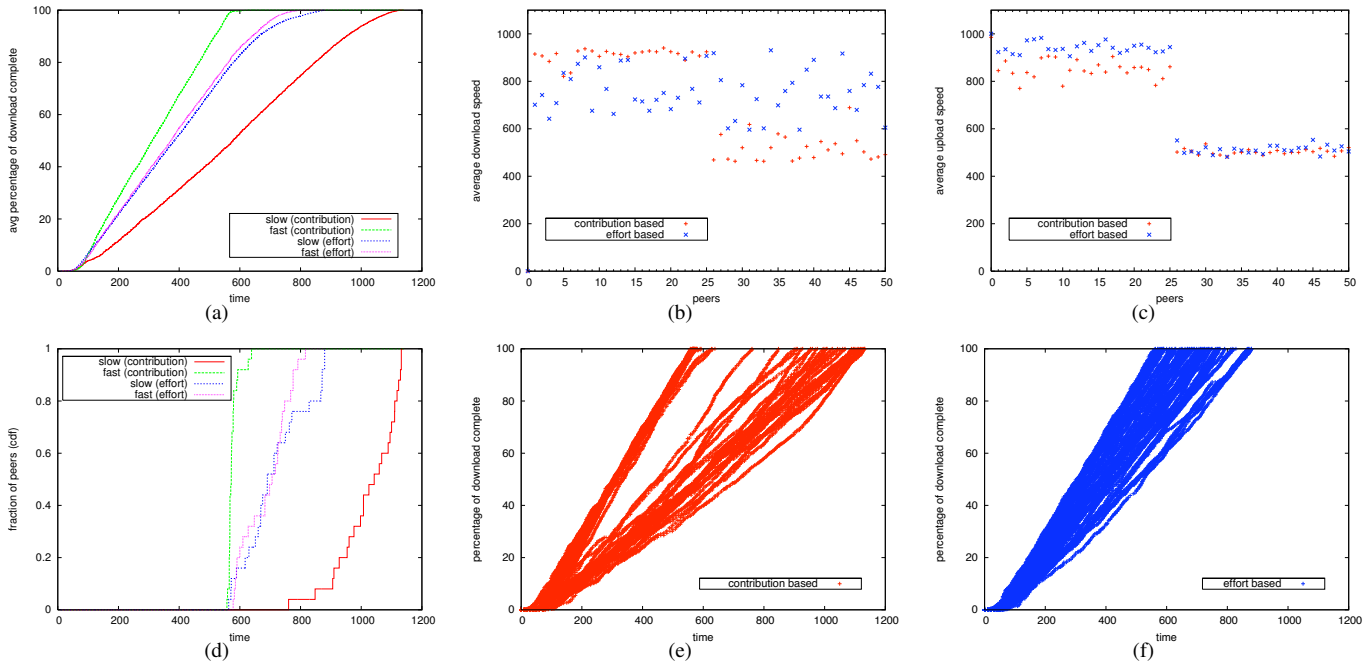

Fig. 2. Various results of contrib and effort BitTorrent simulations with 50% fast peers and 50% slow peers: (a) the download progress over time; (b) the average download speed of all 50 peers ordered on capacity; (c) the average upload speed of all peers; (d) cumulative distribution function of the download finish time; (e) download progress for all peers using the contrib policy; (f) download progress for all peers using the effort policy.

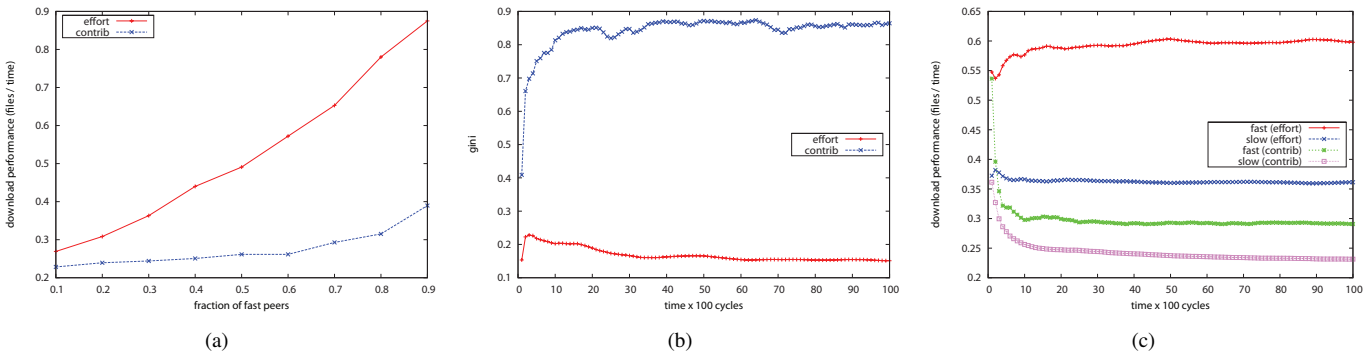

Fig. 3. Various results of contrib and effort Credit Based Scheme simulations (a) avg. download performance of all peers; (b) the gini measure over time with equal proportion of fast and slow peers; (c) the download performance over time of both slow and fast peers, in equal proportion.

A peer can build a positive ratio or earn credits by seeding content to other peers. Sharing ratio enforcement, then, is an incentive mechanism for peers to seed. Seeding is done by peers who stay voluntarily in the network after finishing their own downloads.

If a peer *i* uploads to peer *j*, the former's account is credited while the latter's is debited. A peer can continue downloading only if it has a positive credit (above zero). Thus the total credit in the system will be an invariant C whose distribution over peers will vary with time. In such a scenario, peers with low upload speeds would naturally accumulate less credit as compared to fast peers if both seeded for the same amount of time.

We feel that such systems are ideal candidates for the application of effort-based incentive schemes. If all peers are given credit for the *time* they seed content rather than the amount in megabytes, then all peers could potentially come on a par.

In order to test our hypothesis, we performed experiments using a simplified model of a credit based sharing ratio enforcement scheme. This model is similar to the one described in our previous work [6]. In this model, the community is represented by a set of peers ($\mathcal{P}$). Each peer i has fixed upload (up_i) and download ($down_i$) capacity (in units of data per unit of time). We employ a very simple user model; All peers are online at all times. At any given time a peer is seeding some number of swarms (S) and downloading from some number of other swarms (D). Peers seed files for some fixed amount of time and then remove them from their seeding list. In our experiments we set $D = S = 1$ and the maximum seeding time set to infinity. This means that each peer is always downloading in one swarm and seeding in one other swarm.

For our simulation runs, all file sizes are set to 16 units. Fast peers have an upload capacity of 8 units and download capacity of 16 units. Slow peers have an upload capacity of 2 units and download capacity of 4 units. We ran the simulations on two policies: contribution based contrib and effort based effort. In contribution based policy, each peer earns credit based on its upload speed. So a fast peer earns 8 units (its upload speed) if it seeds a file for one time unit. In the effort based policy, all peers earn the same credit for seeding for one time unit, regardless of their upload capability.

We found that the effort based policy not only leads to a fairer system (lower Gini)[4] but also to a more efficient system in which the overall download performance of all peers increases. (We define download performance as the number of files downloaded by a peer per one time unit.) Fig. (3)(a) and (b) show that the average system efficiency, and fairness increase when the effort based policy is applied. Fig. (3)(c) shows the somewhat startling result that the performance of *both* fast and slow peers goes up under the effort based policy! At first sight, this appears to be inexplicable. However, it can be explained by the fact that rewarding peers according to effort results in an injection of new credits in the system and as we showed in [6], injecting new credits in the system leads to a more efficient system. This is due to the fact that because of extra credit, slow peers are not 'strapped for cash' so to speak, simply because they are slow, and thus are able to download more files, increasing overall system performance.

V. Discussion and Conclusion

In this paper, we explored the use of incentive mechanisms in P2P systems. We argued that generally P2P designers have an inadequate concept of social welfare. Social welfare has been superficially equated with Pareto optimality and efficient outcomes, without a proper analysis of what these entail. We made this analysis and in view of the inadequacy of the standard definition of 'social welfare', we argued for a novel method of incentivizing peers, one that rewards their effort and sacrifice rather than output. This method has been borrowed from Participatory Economics (*Parecon*), which is an alternate economic vision.

Specifically we argued that: most proposed changes to existing protocols, such as BitTorrent, will not lead to Pareto efficient solutions; the broader method of gauging efficiency, the efficiency criterion, depends on *value judgements*; social welfare is the achievement of efficiency under fair and equitable arrangements; and in P2P, remunerating according to effort is a fair maxim of remuneration that has many practical advantages.

Furthermore, we presented simulation results of applying our approach to currently deployed mechanisms. We modified the popular file sharing protocol BitTorrent to reward according to effort. Upon doing so, we made the surprising discovery that rewarding according to effort rather than contribution, makes BitTorrent not only much fairer but also more efficient.

[4]The Gini coefficient [0..1] characterizes inequality with 1 being the most unequal (one peer holds all credit) and 0 being complete equality.

We also applied our approach to a credit based enforcement scheme. Here too, we noticed that rewarding according to effort makes the system both fairer and more efficient.

In the future, we want to test our approach and analyze its feasibility in the presence of freeriders, who are determined to make no effort. Also, we intend to borrow other principles from Parecon for improving the design of P2P systems.

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