This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2010 proceedings

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

Rameez Rahman, Michel Meulpolder, David Hales, Johan Pouwelse, Dick Epema, and Henk Sips
Delft University of Technology
Email: rrameez@gmail.com

***Abstract*—Most P2P systems that have some kind of incentive mechanism reward peers according to their contribution, i.e. total bandwidth offered to the system. 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 effort, i.e. contribution relative to capacity. We make the following contributions: 1) we argue that contribution-based incentive schemes in P2P systems unnecessarily disfavor slow peers and decrease overall system performance; 2) we advocate the use of principles from an alternative economic vision, Participatory Economics (Parecon), to inspire systems to be fair and to ensure maximization of the social welfare while being efficient at the same time, and 3) we present the results of simulations in which we apply 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 a higher system performance and fairness and offers new insights into P2P incentive design.**

I. Introduction

Traditional methods of rewarding peers in P2P systems based on contribution (total bandwidth offered) lead to the welfare of the fast peers and disfavor slow peers. Generally, it has been argued that peers that contribute more should receive better service than those that contribute less [5], [9]. In this paper we apply a new principle of reward to P2P systems, which has been inspired by Participatory Economics (*Parecon*). Parecon is an alternative economic vision in which reward is based on relative contribution or *effort*, defined as the contribution as a fraction of capacity, instead of (the absolute value of) the contribution itself [1]. We argue that this principle (rewarding according to effort instead of contribution) can be adopted to design P2P systems that are efficient while being fair.

Rewarding according to effort, while being incentive compatible, gives both slow and fast peers in the system a level playing field. All peers, regardless of their bandwidth, *can potentially* make the same level of effort. On the other hand, slow peers simply cannot compete with fast peers in terms of output or contribution levels. We argue that systems are fair if they reward effort as opposed to output and hence are equitable to the less resourceful peers.

This work was partially supported by the Future and Emerging Technologies programme FP7-COSI-ICT of the European Commission through the QLectives project (grant no.: 231200) and the P2P-Next project (grant no.: 216217)

P2P systems provide plenty of opportunities for peers to undertake actions that can be characterized as effort. It is a reasonable aim to get peers 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, other forms of 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 only consider effort in terms of bandwidth offered relative to capacity.

In order to validate our approach, we performed 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 does our adaptation lead to more fairness, but even to a higher average system performance. Specifically, in the presence of a high proportion of fast peers, we observe the download speed of slow peers to increase up to 63% at only a marginal 4% decrease in speed for fast peers. Also, in the unmodified BitTorrent protocol, fast peers can achieve as much as 60% higher 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% higher than slow peers.

To verify that our approach can be applied to a variety of systems, we also applied our effort-based reward approach to a generalized credit based sharing ratio enforcement scheme, and show how it positively affects performance and fairness. We observe that rewarding according to effort more than doubles the average download performance of the system. At the same time, the inequality in the system decreases by approximately 80%. 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.

In Section II of this paper, we discuss how the notions of efficiency, fairness, social welfare, and incentives, have been utilized in the literature and implicitly in P2P systems. In Section III *A* we present results from applying effort based rewards to BitTorrent and compare it with the existing protocol. In Section III *B*, we present results from applying effort based rewards to a generalized credit based sharing ratio scheme. We conclude the paper in Section IV, with a summary of our approach and results.

II. Efficiency, Fairness and Incentives

In this section we discuss how incentives have been utilized, and the notions of efficiency and fairness formulated, in the literature and implicitly in P2P systems.

What do system designers want from P2P systems? What kind of economic incentives do they desire? 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 to incentivize peers to contribute their resources to the network. Resources could encompass content, time spent sharing content, and the rate at which content 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]. Indeed in an influential paper, Dash et al. in detailing the desiderata of mechanism design, list Pareto optimality as one of the sought after goals [4]. It is worthwhile to study what exactly Pareto optimality entails.

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 Pareto improvement is possible [12]. Pareto optimality is not necessarily fair [14]. 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* peers better off and *some* peers 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 peers worse off.

Mainstream economists try to circumvent this problem by using an extended concept of efficiency called the *efficiency criterion*, which says 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], [10]. Next, we shall discuss why this equation of social welfare with efficiency is inadequate.

C. More Equity and Less Unfairness

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 and answer, 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 since it is not qualified by a condition of equity.

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, this definition of fairness assumes maxims of remuneration that reward peers for their fast connections. There are two familiar maxims of remuneration [8]:

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 peers 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 utilizes 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 the achievement of efficiency with equity.

D. Participatory Economics

In view of our goal of achieving efficiency with equity, we turn to Participatory Economics (*Parecon*), an alternate economic vision developed by Michael Albert and Robin Hahnel [1]. A comprehensive overview of *Parecon* is available at [11]. 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

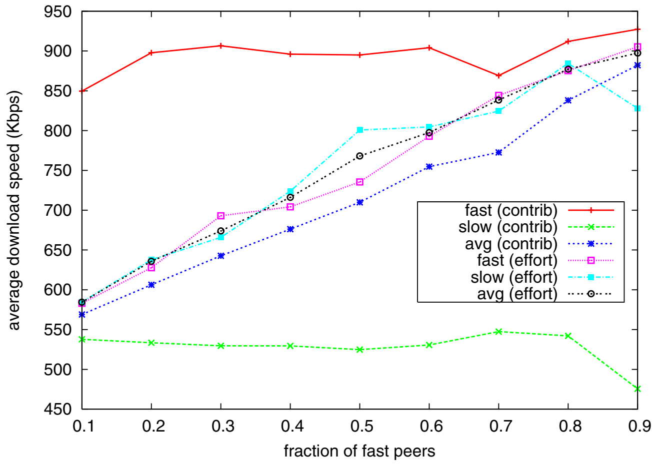

Fig. 1. The download speed of both fast and slow peers in networks with various fractions of fast peers, for the contribution-based policy (contrib) and the effort-based policy (effort) in BitTorrent.

sacrifice that they put into their work, rather than being paid for their output.

We argue that for P2P systems, utilizing this principle can be used to design incentive schemes that are fair, because it ensures that 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 Deployed Mechanisms

In order to assess the efficiency and fairness of effort-based incentive schemes in practice, we applied our approach to two currently deployed mechanisms: the BitTorrent protocol and a generalized credit based sharing ratio enforcement scheme. We observed promising results, with our approach yielding higher efficiency and fairness for both.

A. Efficiency and Fairness in BitTorrent-like Systems

We performed simulations of 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 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 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 peer j. (We note that a secure, efficient, and accurate mechanism to determine the capacities of nodes in a P2P network has been published recently [15].) In addition, in the BitTorrent protocol a peer periodically allocates a slot to a random peer, which we left unchanged.

We simulate systems with swarms of 50 peers consisting of two classes: fast peers with an upload capacity of 1024 Kbps and slow peers with an upload capacity of 512 Kbps, in varying proportions. This polarized view allows us to clearly analyze the effect of a peer's capacity on its performance. Furthermore, we assume that the download bandwidth is not a bottleneck, which corresponds to most realistic BitTorrent systems as most users have highly asymmetric bandwidth capacities [13].

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 observe that under all configurations the average download speed under the effort policy is *higher* than under the contrib policy. The effort 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. When there is a high fraction of fast peers, the download speed of slow peers can increase up to 63% at only a slight loss for fast peers: a 4% reduction in speed. On the whole the average system download speed is greater under all configurations and can increase by as much 10% (Fig. 1).

As expected, effort-based reciprocation is much more fair: compared to the polarized speeds observed with the contrib policy, the effort policy treats slow and fast peers much more evenly. In the unmodified BitTorrent protocol, i.e. the contrib policy, the fast peers can achieve as much as a 60% higher speed than slow peers whereas with the effort policy, the speeds of the two groups, converge to almost identical values, with fast peers reaching speeds only 2% more than slow peers (Fig. 1).

When there are only a few fast peers, these few have to sacrifice a lot in the effort policy 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. Fig. 2 show the properties of both policies in more detail for a system with 50% fast peers and 50% slow peers. The average download completion times of fast peers is nearly 50% shorter than slow peers in the contrib policy, while this difference comes down to almost 5% in the effort policy (Fig. 2a). Importantly, under the effort based policy, an increase of up to 25% in the average upload speed is observed as well (Fig. 2c). Overall, the effort policy leads to higher average upload speed, 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 perfor-

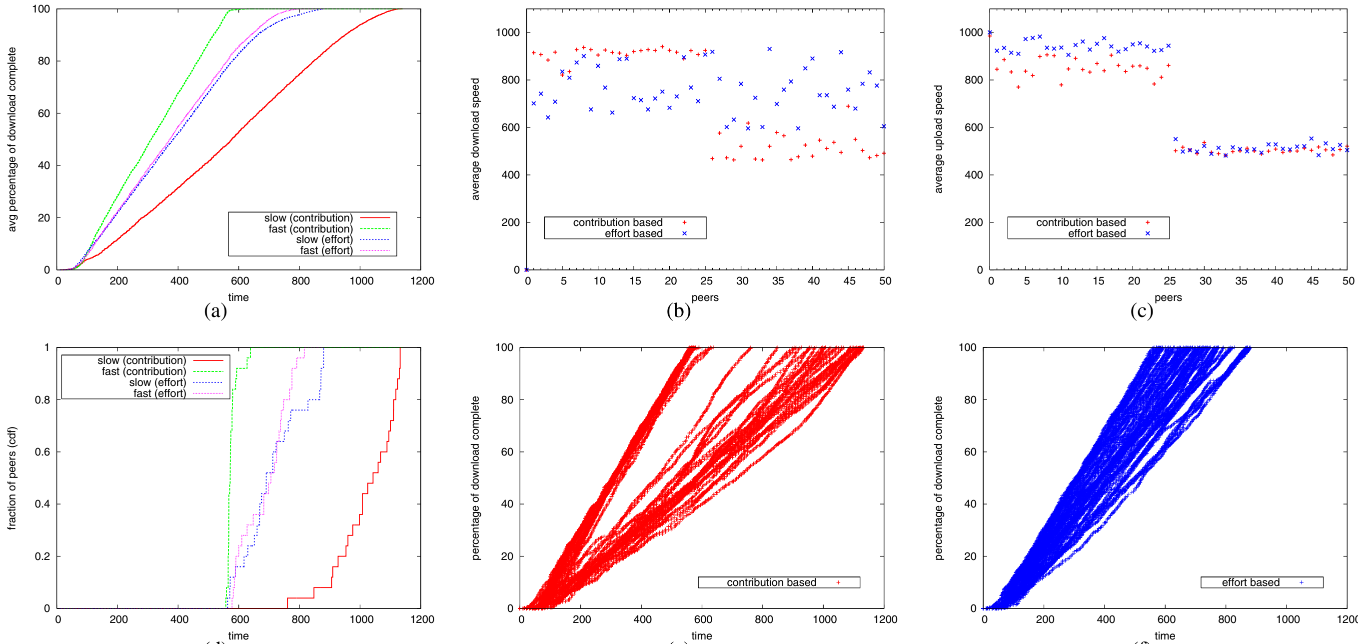

Fig. 2. The performance of the contrib and effort policies in BitTorrent with 50% fast peers and 50% slow peers:(a) the download progress over time; (b) the average download speed of all 50 peers in decreasing order of capacity; (c) the average upload speed of all peers;(d) cumulative distribution function 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.

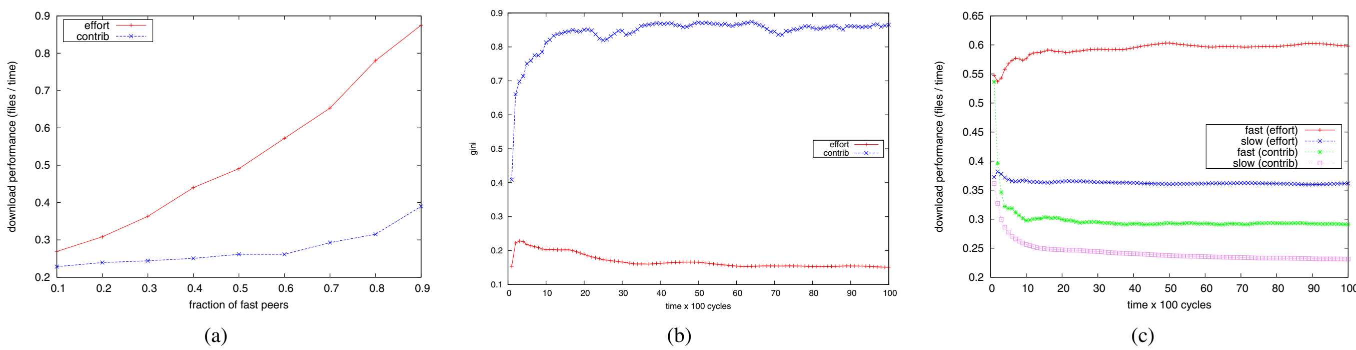

Fig. 3. The performance of contrib and effort policies in Credit Based Scheme (a) avg. download performance of all peers; (b) the gini measure over time with equal proportion of fast and slow peers; (c) the download performance over time of both slow and fast peers, in equal proportion.

mance 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[1].

B. 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. 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 only continue downloading 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. *It should be noted that such credit based sharing ratio schemes are independent of the BitTorrent protocol. Hence, the efficiency and fairness of such systems is solely dependent on credit dynamics.*

We argue that such systems are ideal candidates for the

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

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 [7]. In this model, the community is represented by a set of peers ($\mathcal{P}$). All peers have fixed upload capacities. 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.

We ran the simulations for various file sizes, and various speeds for fast and slow peers. We found that these have no effect on the results. This is because all peers are downloading in one swarm and uploading in another at all times, and the only factor that can affect the difference in efficiency of the fast and slow peers, and credit inequality, is the relative difference in the speeds of fast and slow peers.

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 if a peer has an upload speed of x units per time unit, then it earns x units 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)[2] but also to a more efficient system in which the overall download performance of all peers increases. (Here we have defined download performance as the number of files downloaded by a peer per one time unit.) Fig. 3a and 3b show that the average system efficiency, and fairness increase when the effort based policy is applied. Specifically, rewarding according to effort increased the average download performance of the system by more than 100%. Also, the system becomes much fairer with an approximate 80% decrease in credit inequality.

Fig. 3c shows the somewhat surprising result that the performance of *both* fast and slow peers goes up under the effort based policy! This appears to be counter-intuitive. 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 [7], 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.

[2]The Gini coefficient is a number ranging from 0 to 1 that characterizes inequality with 1 being the most unequal (one peer holds all credit) and 0 being complete equality [6].

IV. Conclusion

In this paper, we explored the use of incentive mechanisms in P2P systems. We argued that rewarding according to effort instead of contribution would lead to systems that are efficient and fair. This principle has been borrowed from Participatory Economics (*Parecon*), which is an alternate economic vision.

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. We observed up to 60% increase in the download speed of slow peers and up to 10% increase in the average system download speed. The huge difference in the download speeds and download completion times between slow and fast peers was also greatly reduced.

We also applied our approach to a credit based ratio enforcement scheme. Here too, we noticed that rewarding according to effort makes the system both fairer and more efficient. The average download performance of the system more than *doubled* and there was approximately 80% decrease in credit inequality.

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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