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Valuation of information and the associated overpayment problem in peer-to-peer systems☆

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ABSTRACT

Most incentive schemes for peer-to-peer (P2P) file-sharing are rate-based, only giving consideration to upload rate when measuring contributions. Besides giving room for strategic peers to benefit from concealing high value chunks, rate-based metrics also aggravate overpayment. Overpayment is a phenomenon that one pays a higher than necessary price for goods. In a P2P system, overpayment exists because in most cases, the incentive schemes have design flaws. Specifically, in rate-based systems, bandwidth allocation policies ignore different values of different chunks, and it directly induces overpayment.

In this work, taking the chunk value in the reciprocity process into consideration, the overpayment problem in a BitTorrent network is investigated, and four side effects of overpayment are identified. A novel strategy called value-based BitTorrent (VBT) is proposed, which is found to be able to alleviate the degree of overpayment and consequently relieve the side effects of overpayment.

1. Introduction

Peer-to-peer (P2P) file-sharing systems have achieved outstanding success during the past two decades, in which every peer not only downloads from the system but also contributes to others. The more a peer contributes to the system, the higher reward it obtains. Incentive schemes therefore plays a crucial role in P2P file-sharing systems. Many different kinds of incentive schemes have been proposed [1–3]. Yet these incentive schemes still have some design flaws, manifested as: (1) loop-holes in policies, and (2) inadequate contribution measurement metrics. Indeed, much recent work has been done in investigating the deficiency of the existing incentive schemes. For instance, BitTyrant [4] and BitThief [5] take advantage of BitTorrent's unchoke policy and optimistic unchoke policy to gain benefit. Levin et al., [6] have tackled this problem, by designing a proportional sharing policy against these strategic behaviors.

We argue that the problem of using inadequate contribution measurement metrics could be an even more acute issue, which is unfortunately largely overlooked in practical systems. As in BitTorrent, most of the existing protocols for P2P systems use rate-based metrics to measure contributions. Specifically, a higher upload rate means a higher contribution level. Consequently, chunk value is neglected in these protocols. Indeed, these existing protocols are designed based on the premise that peers do not care about chunk values, which is unreasonable from an economic point of view. Rate-based metrics actually "motivate" strategic peers to game the system, by under-reporting their chunk maps, because reserving high value chunks can prolong their attractiveness in the long run [6].

Another serious problem about rate-based metrics is that they give rise to overpayment. When a peer pays prices higher than necessary for chunks, it overpays. The existence of overpayment degrades system performance. First of all, the amount of resource a peer overpays others can be used to sponsor other new transactions which can enlarge the system throughput. Secondly, poor peers might be crowded out because rich peers overpay for some chunks, making these chunks too expensive for them to obtain. Moreover, the existence of overpayment distorts the prices of chunks, and further hinders efficient resource allocation. Meanwhile, underpayment is always a consequence of overpayment, because there are peers gain extra advantage when some peers overpay. Thus, alleviating overpayment is critical for both the system and honest peers.

In BitTorrent, peers' contributions are measured by upload rate, without consideration of chunk value. Thus, many low value chunks are overpaid, while many high value chunks are underpaid. Underpayment on high value chunks slows the distribution speeds of high value chunks, degrading the system performance. In [7] and [8],

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chunk related policies are proposed to punish chunk map under-reporters. These works focus on improving the policies. We focus on the devise of one proper measurement indicator and the investigation of overpayment induced by rate-based metrics. We propose a value-based BitTorrent (VBT), in which peers unchoke others by their ranks of aggregated chunk value instead of upload rate to alleviate overpayment.

Another concern about overpayment is how to measure it. We find that, in BitTorrent, the correlation between peers' contributions, measured by aggregated chunk value, and return, measured by the fraction of the file successfully downloaded, shows an interesting pattern, called *light beam pattern* (LBP). Many interesting observations about an incentive scheme can be obtained from LBP. Moreover, we also use LBPs to visualize overpayment and underpayment in P2P file-sharing systems.

In this paper, we make the following contributions:

- Existing policy makers in P2P file-sharing systems all try to encourage peers to contribute more to the system. However, we find quantitatively that the existence of overpayment can degrade system performance and lead to strategic manipulation.
- We find that in BitTorrent, the correlation between peers' contributions and return follows a light beam pattern. Using this pattern, we can evaluate an incentive scheme's degree of overpayment and its resistance to manipulation behaviors.
- We propose two metrics to measure the degree of overpayment for P2P file-sharing systems, and also propose a value-based metric to alleviate the degree of overpayment in BitTorrent. The value-based metric can effectively punish strategic behaviors and alleviate overpayment degree in BitTorrent, leading to much better system performance.

In this work, we analyze the degree of overpayment in a BitTorrent network. We propose a novel value-based metric to value chunks, taking into consideration of chunk rarity. We find that the correlation between peers' investment, which is defined as the aggregate value of chunk they devote, and return, which is defined as the downloaded chunk volume, shows an interesting light beam pattern (LBP). We use LBPs to visualize the degree of overpayment in BitTorrent, compared with our proposed strategy, called value-based BitTorrent (VBT). We find that VBT has a lower level of overpayment and is consequently more robust to chunk map under-reporting behaviors. Our simulation results also show that after alleviating overpayment, the crowd-out effect is also significantly suppressed and the system performance is much better.

This paper is organized as follows. Section 2 provides the system model. A novel value-based metric is proposed to value chunks, taking into consideration of chunk rarity. Game theoretic analysis is used to illustrate the behavior of rational peers when value of chunks are considered. Section 3 illustrates the phenomenon of overpayment caused by rate-based metrics. Section 4 shows that the correlation between peers' investment, which is defined as the aggregate value of chunks they devote, and return, which is defined as the downloaded chunk volume, shows an interesting light beam pattern (LBP). In Section 5, we use LBPs to visualize the degree of overpayment in BitTorrent, compared with our proposed strategy VBT. Section 6 proposes two metrics to quantify overpayment. The simulation results are provided in Sections 7 and 8. Section 9 gives related works. We conclude in Section 10.

2. System model

Most incentive schemes for practical P2P file-sharing applications are rate-based. Rate-based metrics assume that all chunks have an identical value. However, in realistic P2P file-sharing systems, different chunks have different values for both the system and individual peers because of different characteristics of the chunks, e.g., the rarity. The distribution speeds of the rarest chunks in a system are the bottleneck of the distribution speed of a file [9]. Moreover, a peer tends to upload low rarity chunks instead of high rarity ones because concealing high rarity chunks prolongs their attractiveness in the long run [6]. Thus, higher rarity chunks should have higher values. Value of chunks should be considered in the incentive schemes because value of chunks is considered when rational peers making decisions. In this section, a game theoretic analysis is used to illustrate the behaviors of rational peers in strategic P2P file-sharing systems.

Table 1
Prisoner's Dilemma game in BitTorrent.

	Bob uploads high	Bob uploads low
Alice uploads high	$(u_a(H,H), u_b(H,H))$	$(u_a(H,L), u_b(H,L))$
Alice uploads low	$(u_a(L,H), u_b(L,H))$	$(u_a(L,L), u_b(L,L))$

2.1. Prisoners' Dilemma in BitTorrent

Suppose there are two peers, Alice and Bob, connected to each other in BitTorrent. Both of them unchoke each other during a time period. Each peer has a choice of revealing high rarity chunks or low rarity chunks to the other, and thus, each peer's set of action is $\{High, Low\}$. The payoff function u for Alice and Bob are the same. The game is illustrated in Table 1.

In a P2P file-sharing system, possessing more high rarity chunks means larger chance to gain more neighbors, usually leading to a higher download rate. Thus, the benefit of downloading a high rarity chunk is larger than that of downloading a low rarity one. Meanwhile, because uploading a high rarity chunk results in a higher chance to lose more interest among neighbors than uploading a low rarity chunk, the cost of uploading a high rarity chunk is larger than that of uploading a low rarity one. Consequently, Alice and Bob are both very glad to upload low rarity chunks more and downloading high rarity chunks more. Because a rate-based metric is used in BitTorrent for measuring contributions, the other peer will treat it the same no matter whether it uploads high rarity chunks or low rarity ones, provided the rate is the same. As a result, we can easily prove that in BitTorrent, for two collaborating peers, whether to uploading high rarity chunks or low rarity ones is a Prisoners' Dilemma game [10]. This is formalized by the following theorem.

Theorem 1. In BitTorrent, whether to upload high rarity chunks or low rarity ones to their counterparts is a Prisoners' Dilemma game.

Proof. Because uploading a high rarity chunk costs more than uploading a low rarity one, and downloading a high rarity chunk brings more benefit than downloading a low rarity one. Thus, we have $u(H,X) < u(L,X)$, and $u(X,H) > u(X,L)$, X can be H or L.

When both of them uploading high rarity chunks to the other, because the loss in attractiveness can be neutralized by the new chunk it just got, and meanwhile it obtains a high rarity chunk. Thus, the payoff of the two peers when both upload high rarity chunks is larger than that when both uploads low rarity chunks, i.e., $u(H,H) > u(L,L)$.

Thus, we can conclude that: For Alice,

$$u_a(L,H) > u_a(H,H) > u_a(L,L) > u_a(H,L) \quad (1)$$

For Bob,

$$u_b(H,L) > u_b(H,H) > u_b(L,L) > u_b(L,H) \quad (2)$$

Thus, this game is a Prisoners' Dilemma. □

Because it is a Prisoners' Dilemma in BitTorrent, there is only one Nash equilibrium of this game: Both of them upload low rarity chunks to the other. Uploading high rarity chunks will not bring more benefit than uploading low rarity ones, and instead, keeping them might make the peer prolong its attractiveness in the future. If all the rational peers are aware of this, all of them choose to upload low rarity chunks rather than high rarity ones when it has choice. If this happens, high rarity chunks are kept and low rarity chunks are excessively shared. The system performance will then be severely damaged.

2.2. A Value-based metric

The rate-based metric in BitTorrent can lead to conflict-of-interest between individual peer's profit and the system's profit, making peers tend to strategically conceal high value chunks. Thus, the system performance is degraded severely. Because chunk rarity is a crucial factor, making chunks have different importance to the system and individual peers, we propose a simple yet effective value-based metric in which chunk rarity is taken into consideration in the chunk valuation function.

Chunk i's rarity for peer j $r_i^j(t)$ is defined as the reciprocal of its copy number in peer j's neighbor list $c_i^j(t)$. They are all time-dependent variables.

$$r_i^j(t) = \frac{1}{c_i^j(t) + 1} \tag{3}$$

Then, the value of chunk i for peer j $v_i^j(t)$ is defined in Eq. (4).

$$v_i^j(t) = \begin{cases} \log\left(\frac{1}{c_i^j(t)+1} + 1\right), & 0 \le c_i^j(t) < N(t) \\ 0, & c_i^j(t) = N(t) \end{cases} \tag{4}$$

In our system model, a peer calculates one chunk's value according to local information, which means it uses the chunk map information its neighbors reveal to it. Specifically, $N(t)$ is the number of peers in the system at time t. $v_i^j(t)$ is a positive value when there are still peers who do not have this chunk at this time, i.e., $c_i^j(t) < N(t)$. The larger the number of copies of a chunk, the lower its value is. The chunk valuation function is convex, representing the diminishing marginal reduction as the number of chunk copies increases.

Throughout this paper, we use this value-based metric to evaluate peers' contributions to the system. This paper is a preliminary study of the effect of chunk valuation, and only rarity is considered when valuing chunks. There might be many other parameters affecting the value of a chunk. For instance, when a chunk is the last one for a peer to finish downloading a file, this chunk should have higher value to this peer than the other peers. In our another ongoing work, the situation that a chunk has different value functions to different peers is discussed.

2.2.1. Value-based BitTorrent (VBT)

Using the chunk valuation function defined in Eq. (4), we make a slight modification to BitTorrent protocol [1]. Specifically in the new protocol modified from BitTorrent, when a peer unchokes its neighbors, instead of taking into consideration of the upload rate (rate-based) in the previous rounds, it makes decision according to the aggregate uploading chunks' value (value-based) of the neighbors. The contribution function of peer i to peer j in round $t C_j^i(t)$ is:

$$C_j^i(t) = \Sigma_k f_k(t) \cdot v_k^j(t) \tag{5}$$

Note that $f_k(t)$ is the fraction of chunk k peer j got from peer i in round t.

The only difference between VBT and BitTorrent is the contribution function. All other policies, such as rarest first policy, optimistic unchoking policy, are kept the same with BitTorrent. In VBT, peers might still be able to prolong their attractiveness among its neighbors by concealing high value chunks, however, at the risk of losing the unchoking opportunities in the next round.

Table 2
Repeated game in VBT.

	Uploading high value chunks	Uploading low value chunks
Payoff this round	p_h	p_l
Payoff next round	$\alpha \cdot x$	$\beta \cdot x$

2.3. Repeated game in VBT

In VBT, because a value-based metric is adopted, a peer's behavior, uploading high value chunks or low value ones, affects its unchoking results in its neighbors in the next round. Thus, in VBT, it is a repeated game [10]. Peer a's payoff is illustrated in Table 2

Here, α and β are the possibilities that a peer's neighbor will continue cooperating with it for the situations, where the peer uploads high value chunks or low value ones, respectively. Because a value-based metric is adopted, every peer values high value chunks more than low value ones when unchoking its neighbors. Thus, α should be larger than β. The parameter x is the benefit in the next round if peer a can be unchoked. If the peer loses the opportunity of being unchoked in the next round, its benefit in the next round is zero. Thus, the payoffs in the next round when the peer uploads high value chunks and low value ones are $\alpha \cdot x$ and $\beta \cdot x$, respectively.

Notice that p_h and p_l is the benefits of a peer when it uploads high value chunks or low value ones in this round. From the protocol, we know that a peer's behaviors in this round have no impact on its benefits in this round. The behaviors in this round affect the benefits in the next round. Thus, the payoff a peer behaves strategically this round should be larger than it behaves honest, $p_l > p_h$. This is because the long-term interest of preserving chunks. Preserving high value chunks has a higher chance to prolong a peer's attractiveness among its neighbors than preserving low value ones.

If peer a behaves honestly in this round, its aggregate payoff is:

$$p_h + \alpha x \tag{6}$$

If peer a behaves strategically in this round, its aggregate payoff is:

$$p_l + \beta x \tag{7}$$

When we have:

$$p_l + \beta x \ge p_h + \alpha x \tag{8}$$

the peer tends to behave strategically; otherwise, it tends to behave honestly.

From Eq. (8), we can get:

$$(p_l - p_h) \ge (\alpha - \beta)x \tag{9}$$

Thus, whether to behave honestly or strategically, for a rational peer, depends on the profit from prolonging its attractiveness by concealing high value chunks in this round, $(p_l - p_h)$, and the risk of losing unchoked opportunities in the next round due to concealing, $(\alpha - \beta)$, and the profit from being unchoked in the next round, x. For an individual peer, it is very difficult, if not impossible, to predict the result of Eq. (9). However, we can still deduce some useful insights.

If all competitors of a peer have similar upload capacities, which means whether to upload high value chunks or low value ones plays an important role in getting the chance of being unchoked in the next round ($(\alpha - \beta)$ is large), the peer tends to behave honestly. In addition, in a system which has peers with various upload capacities, the poor ones tend to behave honestly because their values of $(\alpha - \beta)$ are large.

On the contrary, suppose there is a very rich peer, in terms of upload capacity, and most of its competitors are poor peers. The difference between its α and β should be very small because VBT is still based on the unchoking policy of the original BitTorrent, i.e., unchoking the top four peers and allocating them the same bandwidth. This peer is rich enough that whether it contributes high value chunks or low value ones makes no difference on its rank among its neighbors. What should be clarified is that this only happens when most of the competitors are far poorer than it.

3. Overpayment

One important problem with rate-based metrics is that they aggravate overpayment in P2P file-sharing systems. When there are peers who pay prices higher than necessary for chunks in a system, we say that there is overpayment. Overpayment might cause system performance degradation and strategic manipulation. We then use an example to illustrate the negative effects of overpayment.

3.1. Illustrative example

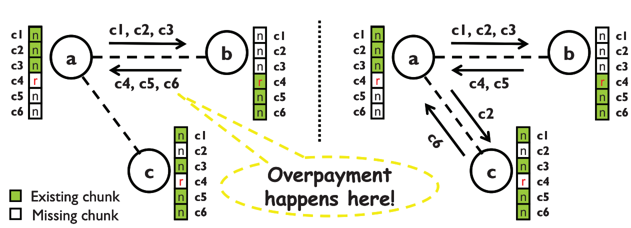
In Fig. 1, a and b are high upload capacity peers, but c is a low upload capacity peer. There are six chunks for the file shared in the system: $(c_1, c_2, c_3, c_4, c_5, c_6)$. Very rare chunks are marked by $\boldsymbol{r}$, and normal chunks, compared with very rare chunks, are marked by $\boldsymbol{n}$. In scenario (a) peers use a rate-based metric, while in scenario (b) peers use a value-based metric, considering rarity by using the value function defined in Eq. (4).

In scenario (a), b overpays a, and because of this, c is crowded out by being deprived of the opportunity of trading with a. After a value-based metric is adopted, in scenario (b), b pays (c_4, c_5) to a instead of (c_4, c_5, c_6). Because c_4 is a very rare chunk, thus it is enough to pay (c_4, c_5) to a for (c_1, c_2, c_3). Thus, c obtains the opportunity to get involved in the transactions. In addition, the system performance is better. The contributions to the system are now $c_1, c_2, c_2, c_3, c_4, c_5, c_6$, one more copy of c_2 than in scenario (b).

The example is designed to illustrate the phenomenon of overpayment when a rate-based metric is adopted. For the sake of understanding, a "rigid" tit-for-tat is adopted in the example. Though BitTorrent does not employ a rigid tit-for-tat as in the example, the idea about overpayment alleviation when a value-based metric is adopted is the same.

3.2. Negative effects

Aggravate crowd out effect. The peer who overpays might crowd out other peers, especially less privileged peers, which might involve in the transactions if it does not overpay, leading to performance loss to other peers and the system. Less privileged peers are crowded out for two reasons. Firstly, overpayment leads to too high prices for some chunks, which they cannot afford. Secondly, overpayment saturates the demands of many peers, which can provide trade opportunities for less privileged peers if these peers were not overpaid.



(a) Rate based (b) Value based

Fig. 1. Illustration of overpayment.

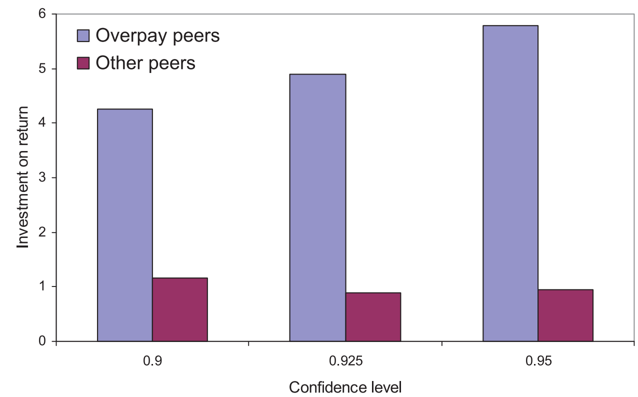


Fig. 2. Investment-on-return comparison.

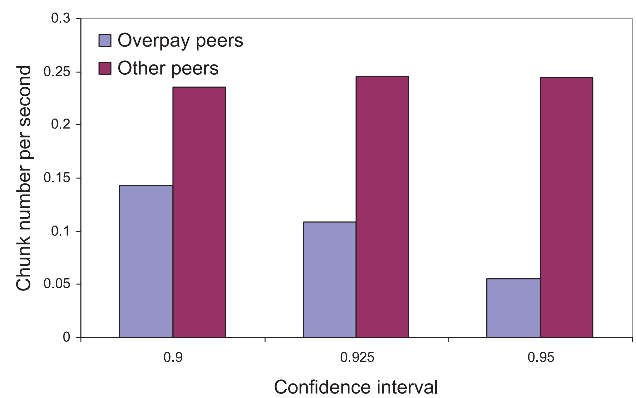


Fig. 3. Average download rate comparison.

Inefficient resource allocation. Overpayment "wastes" resource to propagate low value chunks in the system, accordingly "decreasing" the propagate speed of high value chunks. From Legout et al.'s work [9], we know that high value chunks' distribution speeds are crucial for BitTorrent's performance. Moreover, too much resource is allocated to low value chunks and too little resource is left to high value chunks, resulting in inefficient resource allocation.

Individual peers suffering from overpayment. The peer who overpays itself also suffers from overpayment, because it can obtain other chunks by the amount of payments it overpays or just save cost for obtaining these chunks. Overpayment peers get worse performance than ordinary peers instead of benefiting from overpaying others.

We compare the performance of peers who overpay and peers who do not overpay in a BitTorrent network. Fig. 2 shows the comparison of investment-on-return between overpay peers and other peers. Investment-on-return indicates the average payment for an individual chunk. Fig. 3 shows the comparison of average download rate. It is obvious that overpay peers pay further higher for an individual chunk than peers who do not overpay, but their average download rate is even lower than the peers who do not overpay. This indicates that in BitTorrent, when peers overpay, instead of getting a better performance, they get a worse performance than the other peers. This is probably because when peers overpay others, they waste the payment which can be used to obtain other chunks, and they might lose the interest of their neighbors quickly because they contribute their resource too fast.

Encourage strategic behaviors. The only beneficiary is the peer who underpays, and this is the reason for another negative effect of overpayment: there is space for peers behaving strategically instead of behaving honestly in incentive schemes which allow overpayment. The existence of overpayment shows the coexistence of underpayment. Strategic peers may game to benefit from underpayment. In rate-based incentive schemes, uploading a high value chunk and uploading a low value chunk will be considered as the same contribution. Thus, strategic peers tend to under-report chunk map to prolong their attractiveness [6].

In Section 7, we will study the above negative effects of overpayment in BitTorrent and the improvement of VBT by experiments.

4. Correlation between return and investment

Overpayment is related to peers' payment and gain. In order to measure overpayment degree for an incentive scheme, we will firstly investigate the relationship between peers' contributions and return.

4.1. Light beam pattern

We conduct the experiments using the well-known BitTorrent simulator provided by [11], which is also used by many BitTorrent studies. There are one thousand peers joining in the system, following a Poisson join pattern, with the average join rate of 2 peers per second. There is one source seed whose upload capacity is 1000 Kbps, staying in the system throughout the simulation. The file shared is 100 MB and equally divided into 400 chunks. We use the bandwidth distribution in Table 3 which is derived from the actual distribution of Gnutella nodes [11,12]. Peers leave the system as soon as they finish downloading the whole file, or, they quit because of starvation. If a peer cannot download anything at all for a certain period of time, which we call *tolerance range*, it will leave the system. The simulation is run until all peers leave the system. All the experiments in this paper use the same configuration unless otherwise specified.

Based on the game theoretic analysis in Section 2 and the experiment results in [6], rational peers are not willing to upload high value chunks unless they are motivated. Moreover, high value chunks' distribution speed is much more important than that of low value chunks [9]. Thus, we use aggregated chunk value instead of rate to measure peers' contributions to the system. Fig. 4 is the correlation between contributions and return we obtained. The ordinate value is aggregate contributions in terms of chunk value, and the abscissa value is the number of chunks one peer successfully downloads when it leaves the system. Every peer ever involved in the system has a point in the coordinate plane. Each peer has an investment-on-return (IOR) value which is the gradient of the line connecting the original point and the point belongs to it in the coordinate plane. There is an explicit correlation between aggregate contributions and return in BitTorrent. The shape of the correlation looks like a light beam. Its width is very small at the beginning, very close to zero at the origin point, and diverges as it travels far, leading to its name: *light beam patten* (LBP).

Table 3
Bandwidth distribution.

Fraction	Uplink (Kbps)	Downlink (Kbps)
0.2	128	784
0.4	384	1500
0.25	1000	3000
0.15	5000	10000

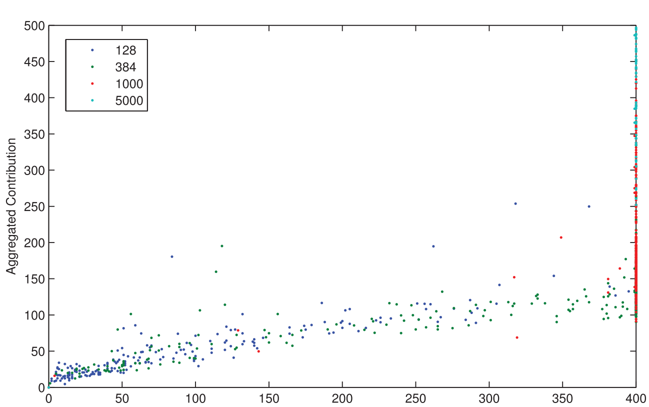


Fig. 4. The LBP in BitTorrent.

Why using this departure pattern? The overpayment degree of one incentive scheme is about peers' contributions and return. One single case of any time point cannot prove anything, because the downloading situation of the system is a dynamic process. In the BitTorrent application, the program sets it as default that peers do not leave the system until they finish downloading. However, seeding for a long time without downloading any chunks is not realistic if peers have choice to make. In addition, an effective incentive scheme should promote better transaction without the situation of "seeding for long time". Thus, we use the departure pattern to obtain the correlation map of contribution and return to investigate overpayment. When tolerance range varies from 10 s to 2 min, the correlation maps all show light beam pattern, with the only difference about the distribution density of the points in different regions of LBP. Due to the limit of space, we omit simulation results. To reduce the influence of different seeding time of peers to the correlation of contribution and return, we use the tolerance range (10 s) in this paper.

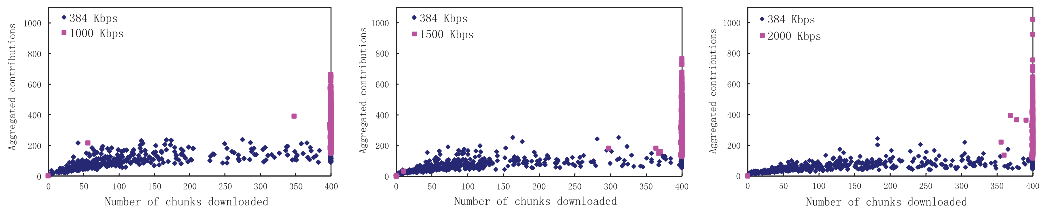
4.2. Two parts

Points gathering at the beginning of the light beam belong to peers who are crowded out from the system at a very early stage. Most of them are low upload capacity peers. On the contrary, points gathering at the projection of the light beam (x axis values equal to 400) belong to peers who successfully download the whole file. Thus, LBP actually includes two parts: the *projection* which consists of peers who finally download the whole file, and the part except the projection which consists of peers who are crowded out because of starvation (we name it *light beam*). When all the conditions keep the same, a better incentive scheme should have smaller divergence effect than others, which means smaller projection length and narrower light beam width.

Peers who are crowded out (light beam) At the early stage of downloading, a good incentive scheme should not allow too large gap in IOR. Because larger difference means higher level of unfairness, under which some peers might pay a lot but end up with very little gaining, while others might pay very little but end up with gaining a lot. As the download process goes far, the differences among peers' IOR accumulate, and the width of light beam grows. Apparently, a good incentive scheme can keep the grow rate under a very low level.

Peers who successfully obtain the whole file (projection) The length of the projection indicates the span of IORs of all the peers who successfully downloaded the whole file. Many factors affect the length of the projection. The wealth gap, which is the largest difference about upload capacity among peers in the system, is one major cause. When the wealth gap increases, the length of the projection increases, keeping other conditions the same.

When wealth gap varies Fig. 5 are the LBPs for three scenarios, with the wealth gap increasing one by one. There are two kinds of peers in each scenario, with each kind of peers occupying half of the population. The projection of LBP increases as the wealth gap increases. The lower bound of the projection is becoming lower as the wealth gap increases, due to the increasing assistance from high upload capacity peers to low upload capacity peers. The upper bound of the projection becomes higher as the wealth gap increases, due to the increment of high upload capacity peers' upload capacity. The light beam divergence degree becomes smaller as the wealth gap increases. The main reason is that the population of peers who are



(a) (384,1500) & (1000,3000) (b) (384,1500) & (1500,3500) (c) (384,1500) & (2000,4000)

Fig. 5. LBPs when wealth gap increases in BitTorrent. (384,1500) represents peer group whose upload capacity is 384 Kbps and downloading capacity is 1500 Kbps.

crowded out shrinks, due to the increasing assistance from high upload capacity peers.

5. Investigate overpayment using LBP

Theoretically, the rate-based metric in BitTorrent aggravates the degree of overpayment. In this section, we use LBP to compare the degree of overpayment in BitTorrent and VBT.

5.1. LBP and overpayment

In the ideal scenario, where all the peers have symmetric resource (the same bandwidth condition, the same neighborhood condition, the same welfare from the seed, the same chunk map evolution during downloading process), an ideal (no overpayment) incentive scheme's LBP should be a line, which means that all the peers have the same investment-on-return (IOR). However, in realistic scenarios peers have asymmetric resource. Although bandwidth condition can be the same, the evolution of neighborhoods and chunk maps are too difficult, if not impossible, to be identical. Moreover, a robust incentive scheme is supposed to motivate peers to contribute more. Rigid fairness is not good for system efficiency. We agree with the definition of fairness in [6]: devote more, gain more.

Thus, we relax the definition of "no overpayment" in realistic scenarios. In a P2P file-sharing system, when there is no overpayment, the LBP should have smooth bounds, both the top one and the bottom one. The more jagged the bounds are, the more overpayment/underpayment there is. The realistic meaning is that, most of the peers have similar IOR, they are mostly in a region, have a bottom bound and an top bound. As for the ones whose IORs are out of this region, we call larger ones overpayment peers, and we call smaller ones underpayment peers. The farther their distances from the bounds are, the more serious the overpayment/underpayment they have achieved. Under this definition, in a system adopting an incentive scheme which leads to no overpayment, every peer involved in is motivated to devote more with the confidence of gaining more, because in a system with no overpayment, devoting more should lead to the result of gaining more.

5.2. When all peers are honest

In this section, all peers behave honestly. The overpayment of BitTorrent and VBT is visualized using LBP. The experiments in this section use the configuration in Section 4.1.

Comparison of projection Table 4 shows that VBT has shorter projection, which means the gap between the lowest investment and

Table 4
Projection comparison.

	BitTorrent	VBT
Lower bound	82.82	90.97
Upper bound	1609.62	1531.33
Length	1526.80	1440.36

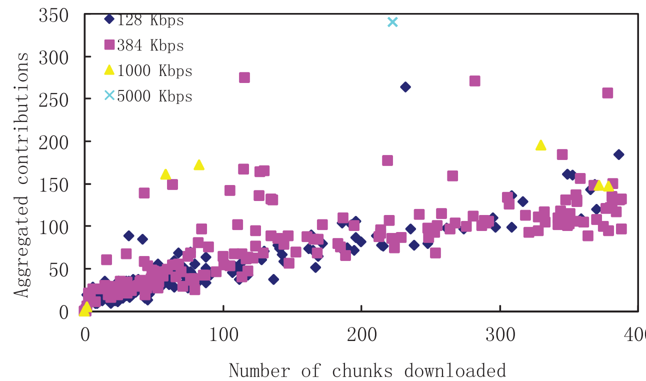


Fig. 6. Light beam of BitTorrent.

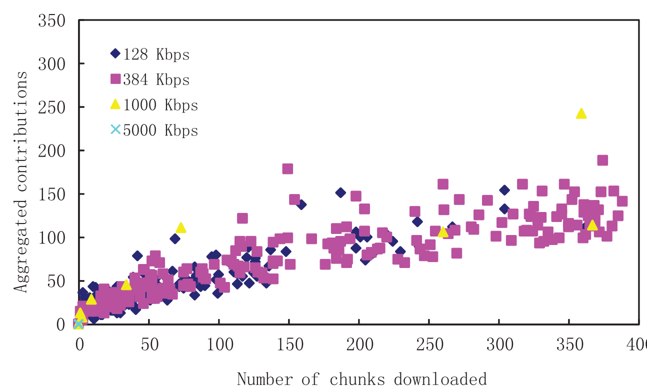


Fig. 7. Light beam of VBT.

highest investment in obtaining a whole file is smaller, indicating a lower level of divergence effect of the LBP than BitTorrent.

Comparison of light beam From Figs. 6 and 7, we can see that there are more overpayment cases in BitTorrent than in VBT. In BitTorrent, many peers are forced to leave the system because of starvation at the early stage of downloading, although they have paid much higher than other peers. Due to the adoption of the rate-based metric, even if some peers contribute a lot of high value chunks, they still have chance to be crowded out from the system because their contributions are measured by upload rate. In the opposite, the peers who contribute more in terms of aggregate chunk value can be better guaranteed to get higher performance in VBT.

Linear regression analysis To further corroborate the conclusion we get above, we use linear regression method to analyze LBPs of BitTorrent and VBT. Table 5 shows the linear regression results. The first four statistics are used to measure the goodness of fit of linear regression analysis for LBP. For SSE (sum of squares due to error) and RMSE (root mean square error), a value closer to 0 indicates a better fit. For R-square (coefficient of multiple determination) and adjusted R-square (degree of freedom adjusted R-square), a value closer to 1 indicates a better fit. In VBT, all the four statistics indicate a better

Table 5
Linear regression analysis results.

	BitTorrent	VBT
SSE	6.03E+07	4.14E+07
R-square	0.1887	0.2402
Adjust R-square	0.1879	0.2394
RMSE	245.6	203.4
Correlation Coefficient	0.4344	0.4901

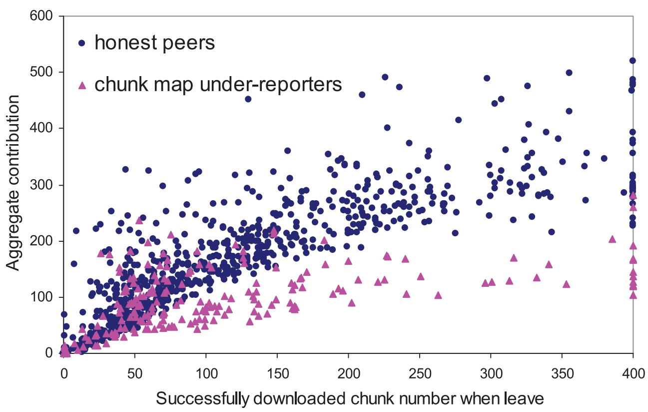


Fig. 8. LBP of BitTorrent.

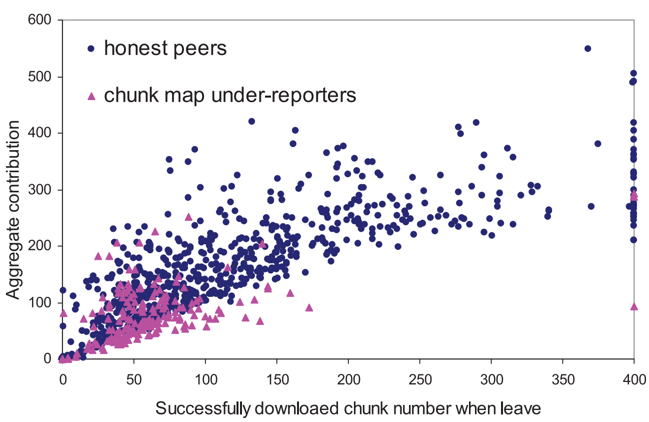


Fig. 9. LBP of VBT.

fit than in BitTorrent. Correlation coefficient indicates the strength of the linear relationship between investment and return in LBP. A value closer to 1 indicates the relationship is stronger, and a value closer to 0 indicates the relationship is weaker. VBT has a stronger linear relationship than BitTorrent.

Thus, in VBT, Overpayment degree is alleviated, and peers who contribute higher value chunks are better guaranteed to get better performance. Peers in VBT are better motivated to devote high quality chunks to the system than in BitTorrent.

5.3. When strategic peers exist

There are 20% peers who under-report their chunk maps. To ensure a clearer elaboration, we use a homogeneous bandwidth distribution, in which there is only one kind of peers: (384 Kbps, 1000 Kbps). In BitTorrent, Fig. 8 shows that strategic peers have similar pattern with honest peers, and strategic peers obviously underpay for their gain than honest peers. However, in VBT, almost all strategic peers are crowded out from the system at the very early stage in Fig. 9. About 90% cheaters leave before they can download 100 chunks. Only very few strategic peers can finally obtain the whole file, which is mainly due to the assistance from the source seed and the optimistic unchoking policy.

6. Quantify overpayment

Using LBP, peers whose points are above the top bound of the light beam are those who overpay, and peers whose points are below the bottom bound of the light beam are those who underpay. Now problem is, how to identify the top and bottom bounds of the light beam? In this section, we use confidence interval to identify the two bounds of the light beam, and propose two metrics to quantify overpayment. Then, we use the proposed metrics to compare the overpayment degree in BitTorrent and VBT.

6.1. Identify bounds using confidence interval

In LBP, every peer has a point in the coordinate plane, and a gradient of the line which connects the point and the original point. we call the gradient "investment-on-return" of peer i, denoted by IOR_i. Most peers in LBP have *IOR* distributed in an interval. We use confidence interval to identify this interval.

We explain the calculation of confidence interval of all peers' IOR in LBP by the example of BitTorrent. Firstly, the histogram of the *IOR* values of all the peers is drawn, as shown in Fig. 10. From the histogram we can see that it is not a symmetric distribution. Thus, we use an iterative optimization technique with the aid of Matlab to obtain the shortest confidence interval.

After the confidence interval is obtained at some confidence level, two lines are drawn from the original point with the gradient equal to the upper bound value and lower bound value of the confidence interval, respectively. Thus, the points out of the bounds in LBP belong to peers who overpay and underpay during the downloading process.

6.2. Metrics to quantify overpayment

6.2.1. Confidence interval

At different confidence levels, different confidence intervals can be obtained. When confidence level is the same, shorter confidence interval indicates smaller divergence of LBP. A light beam whose divergence degree is lower means its overpayment degree is also lower.

6.2.2. The extent of overpayment

At a certain confidence level, the peers whose IORs are above the upper bound of the confidence interval are overpay peers, and the

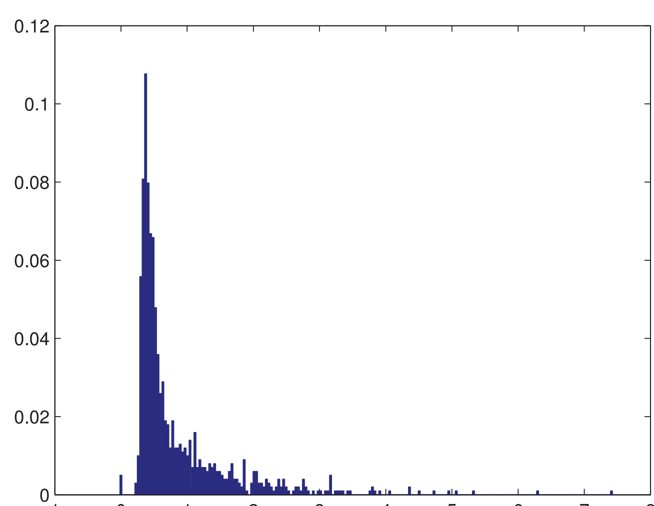


Fig. 10. Histogram graph of IOR distribution.

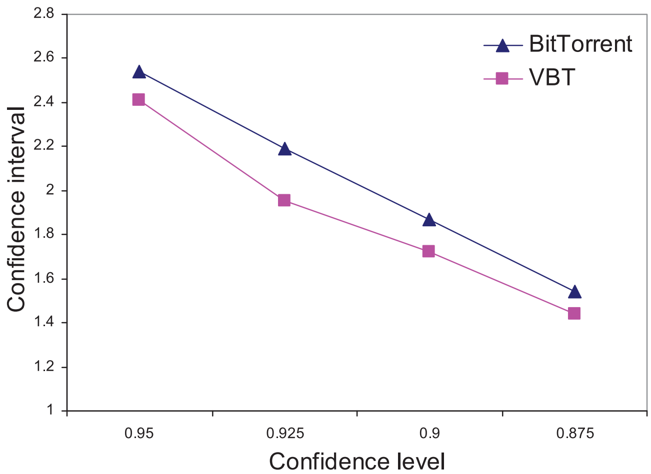


Fig. 11. Comparison of confidence interval.

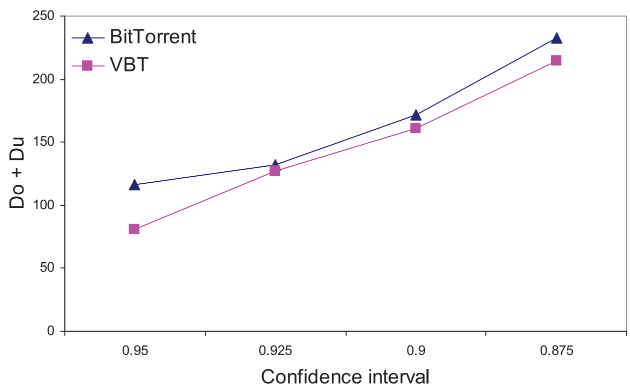


Fig. 12. Comparison of overpayment extent.

peers whose IORs are below the lower bound are underpay peers. We denote the upper bound of the confidence level c_h, and the lower bound c_l. Thus, the overpayment degree D_o and underpayment degree D_u can be represented as in Eqs. (10) and (11).

$$D_o = \sum (IOR_i - c_h)^2 \tag{10}$$

$$D_u = \sum (c_l - IOR_i)^2 \tag{11}$$

Overpayment degree D_o is the aggregate square of the difference between the overpay peers' *IOR* and the gradient of the top bound of the light beam. Underpayment degree D_u is the aggregate square of the difference between the underpay peers' *IOR* and the gradient of the bottom bound. We use them to depict the extent of overpayment.

6.2.3. Overpayment comparison

Using the metrics proposed in the previous section, we compared the overpayment degree of BitTorrent and VBT, which are shown in Figs. 11 and 12. The confidence intervals are shorter in VBT than in BitTorrent. This indicates that VBT has a stronger correlation between investment and return. The overpayment extent has also been relieved in VBT. In BitTorrent, many peers who overpay others are crowded out from the system, because they are not rewarded for their high quality contributions. After the value-based metric is adopted, high quality contributions are rewarded, which makes the overpayment extent relieved.

7. Performance analysis

After the value-based metric is applied, the degree of overpayment can be relieved. In this section, we would further verify three questions. Firstly, after overpayment is alleviated, is the crowd out effect also alleviated? Secondly, after overpayment is alleviated by using the value-based metric, does the resource allocation become more efficient? In other words, whether or not the system can benefit from alleviating overpayment? Thirdly, can the value-based metric effectively suppress the strategic behavior of gaming the system by only contributing low value chunks?

7.1. Population size investigation

Population size is a very important indicator to assess the performance of an incentive scheme. A good incentive scheme should have ability to maintain good population size, which means the number of peers crowded out from the system is small.

In BitTorrent, not all joined peers can finally obtain the whole copy of the file. Many peers are crowded out because of different reasons. The most important reason might be that some peers cannot get a reasonable downloading speed for a relatively long time. Apparently, a poor peer have a higher chance to be crowded out from the system, because its small upload capacity makes it not be able to provide as high upload rate as a rich peer does. Although it is always true that rich peers would get better performance than poor ones in a distributed system, it is not the main intention to design an effective incentive scheme. A good motivation is supposed to aim at making all the peers who contribute more obtain more, not depriving the poor ones' right to involve the game by crowding them out.

In this section, we first show that peers could be crowded out in a BitTorrent network. The crowd out effect degrees of different categories of peers will also be illustrated. After that, the population sizes of BitTorrent and VBT are compared.

7.1.1. Crowd out effect

We use two departure patterns to verify this assumption. There are two runs using BitTorrent protocol. In the first one, peers keep staying in the system until they finish downloading the whole file, even if it takes them very long time. In the second run, peers leave the system if they cannot download anything for a period of time (10 s). Fig. 13 shows the result of the first run. The population size shows a Poisson like pattern, corresponding to the Poisson join pattern. Fig. 14 shows that when peers leave because of impatience, the population size decreases. Fig. 15 shows that the smaller the upload capacities, the larger the decrement percentages. The decrement percentage is defined as the ratio of the difference between the average population size of the first run and the average population size of the second run to the average population size of the first run. Obviously less privileged peers have more chance to be crowded out from the system. Fig. 15 also shows that peers with an upload capacity of 5000 Kbps have a higher population decrement percentage than that

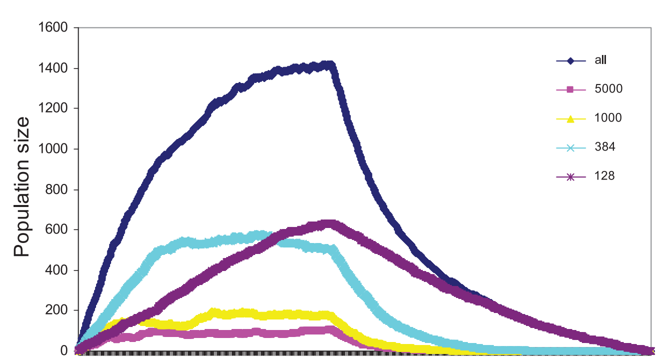


Fig. 13. Peers stay until getting whole file.

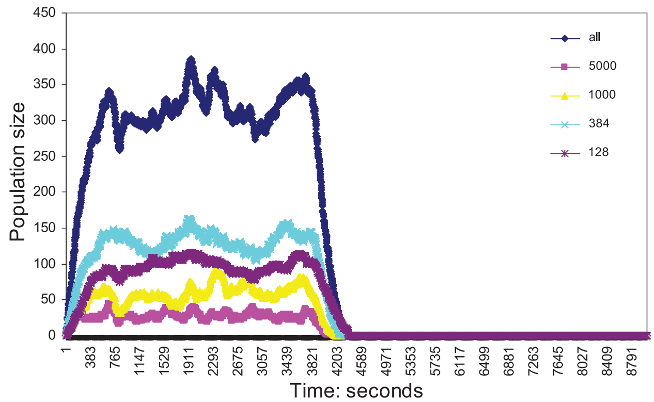


Fig. 14. Peers leave for impatience.

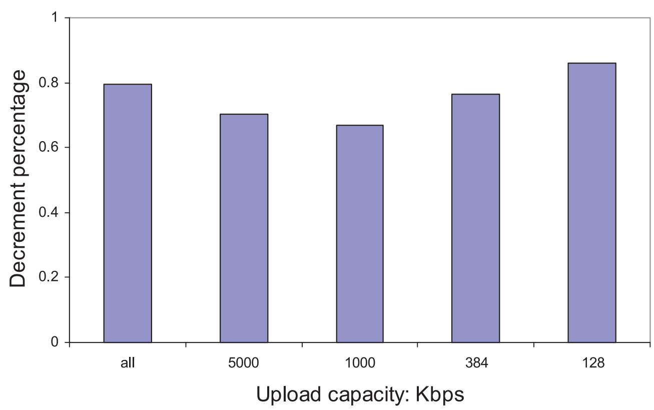


Fig. 15. Population size decrement percentages.

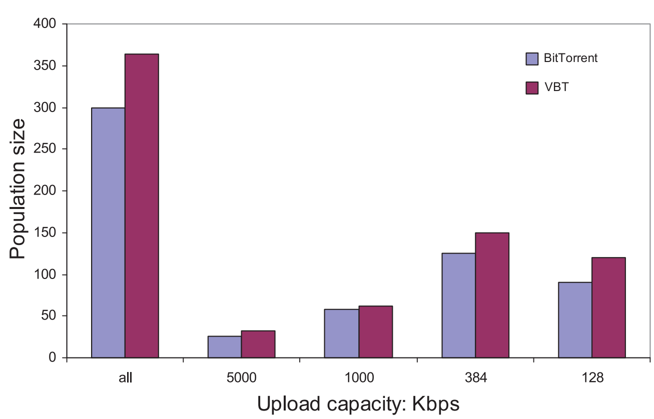


Fig. 16. Comparison of population size.

of peers with an upload capacity of 1000 Kbps. This is because peers with an upload capacity of 5000 Kbps upload with too high upload rates, making them lose their attractiveness among their neighbors too soon. These peers will soon encounter a situation that they have no chunks which their neighbors are interested in, even if their upload capacities are high.

7.1.2. VBT's population size is better

Population size is the number of peers who participate in the system at a certain time instant. We record the population size every 10s. The average population size is the mean of population size over time. Fig. 16 shows that the average population size of VBT is about 20% percentage better than that in BitTorrent. The population sizes of four categories of peers are all better, especially that of the less privileged peers. Thanks to the adoption of the value-based metric, the degree of overpayment is alleviated in VBT, relieving the crowd out effect correspondingly. Moreover, in VBT, poor peers also can obtain high value chunks because value of chunks is emphasized when measuring contributions which weakens the emphasis on upload capacity. Thus, after the value-based metric is applied, the increment of poor peers population size should be more obvious than rich peers.

7.2. Resource allocation efficiency improvement

Overpayment wastes resource on low value chunks and makes high value chunks lack enough emphasis in the system, making the resource allocation inefficient. In this section we use two metrics to measure the efficiency of resource allocation in P2P file-sharing systems.

Success rate: Success rate is the fraction of peers who finally obtain the whole file in the population.

Average downloaded fraction: In BitTorrent, even if a peer is crowded out from the system, it can resume its downloading by rejoining in. Thus, the average downloaded fraction of the file through all the peers when they leave the system is also an important indicator to access system performance.

Fig. 17 shows that, compared to the situation in BitTorrent, low upload capacity peers get better performance while high upload capacity peers get worse performance in VBT. In other words, after the value-based metric is applied, the performance gap between high upload capacity peers and low upload capacity peers becomes smaller. Although the rich peers' welfare is degraded slightly in VBT than in BitTorrent, it is still relatively high. Fig. 18 shows that VBT's performance is obviously better than BitTorrent's.

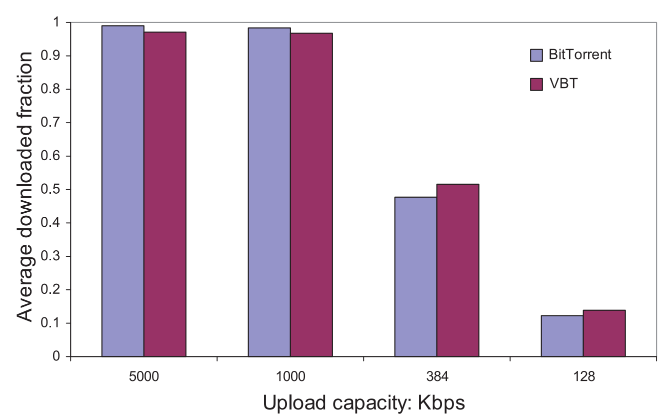


Fig. 17. Average downloaded fraction.

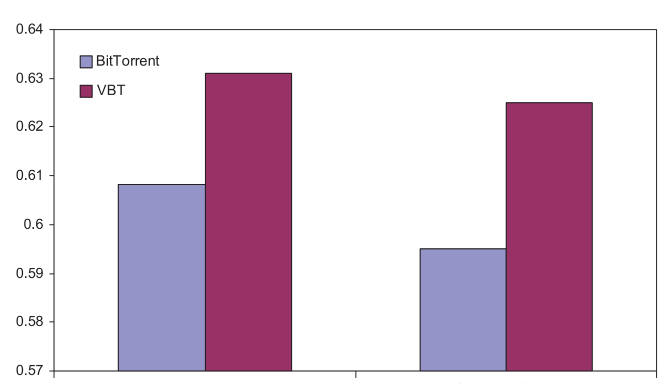


Fig. 18. Performance comparison.

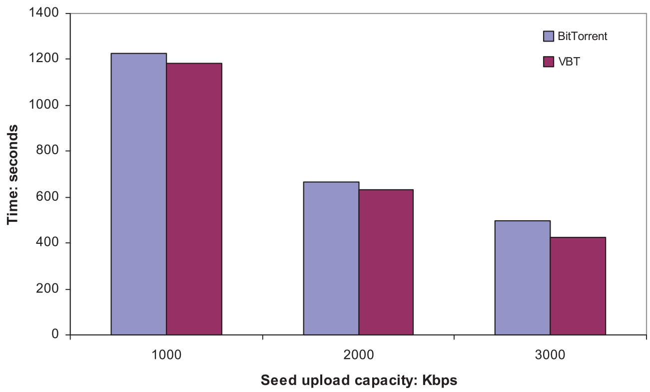


Fig. 19. The distribution time comparison.

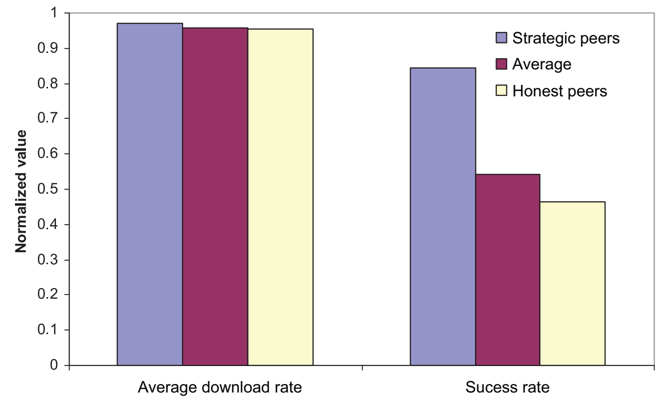


Fig. 20. Performance comparison in BitTorrent.

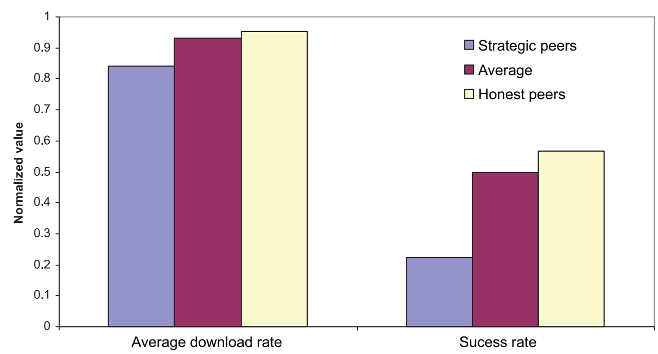


Fig. 21. Performance comparison in VBT.

7.3. The distribution speed of the very FIRST copy of the file

In a realistic system, the distribution speed of the very first copy of the file is crucial for system robustness, because seeds can leave the system at any moment. When people download some files using BitTorrent, what happens very often is the downloading process abruptly stops and cannot be resumed when the download is almost finished. A most likely cause is that all the seeds have left the system, and among all the leechers in the system, there is not a whole copy of this file. Some chunks can never be downloaded because of the lack of a complete copy of the file. Indeed, the faster the distribution speed of the very first copy of the file is, the more robust the system is.

There is only one seed in the system, and the upload capacity of the seed varies from 1000 to 3000 Kbps. All the peers here are honest peers. Fig. 19 shows that VBT always has shorter distribution time of the very first copy of the file than BitTorrent. In VBT, peers who have more high value chunks are emphasized, and thus can get more good neighbors who have high upload capacities and large amount of chunks. A high value chunk therefore gets a higher chance to be distributed. Thus, in VBT, there are more transactions about high value chunks than in BitTorrent, resulting in faster distribution of the very first copy of file.

7.4. Chunk map under-reporting behaviors

In this section, we investigate the following problem: can the value-based metric effectively suppress the strategic behavior of gaming the system by only contributing low value chunks?

Peers tend to under-report their chunk maps to seek higher profits in BitTorrent, because its attractiveness can be prolonged and their contributions are measured by upload rate instead of aggregated chunk value. According to [6], a chunk map under-reporter only updates new chunk when its neighbor loses interest towards it. It selects the chunk with the smallest value, which is the most common chunk in its existing chunk map and in the neighbor's interest chunk map. Thus, the chunk map under-reporter can prolong its neighbors' interest in it and underpay its collaborated peers. Using this strategy, the aggregated chunk value it uploads to others is as small as possible, because it always only updates the chunk with the lowest value in its neighbors' interest map.

7.4.1. Resilience against strategic behaviors

There are 20% peers set to be strategic peers. Fig. 20 shows the comparison of *average download rate* and *success rate* of honest peers (peers who honestly report their chunk map) and strategic peers (peers who under-report their chunk map) in BitTorrent. Fig. 21 shows the comparison of *average download rate* and *success rate* of honest peers and strategic peers in VBT. Here, *Success rate* means the fraction of peers who finally successfully get the whole file in the population.

In BitTorrent, strategic peers have higher average download rate and success rate than honest ones. This implies that if one peer behaves strategically, the expected download rate and the possibility of successfully getting the whole file are higher than behaving honestly. From this point of view, BitTorrent actually motivates peers to behave strategically. On the contrary, VBT effectively punishes strategic peers. Both the average download rate and success rate of strategic peers are much lower than honest peers.

In this scenario, thanks to the punishment towards strategic behaviors, the average performance for all peers and average performance for honest peers are degraded in VBT than in BitTorrent. In contrast, in BitTorrent, strategic behaviors are rewarded instead of being punished. Strategic peers suffer from very bad performance in VBT instead of benefiting in BitTorrent, and thus, all peers in VBT tend to behave cooperatively. When all peers behave cooperatively, the experiments show that the performance is better in VBT as shown in Fig. 18.

7.4.2. When the fraction of strategic peers varies

Considering that strategic peers might cause certain degree of chunk value distortion, we test the punishment effect of VBT towards strategic peers when the fraction of strategic peers varies. Fig. 22 shows that when the fraction of strategic peers varies from very small, 5%, to very large, 80%, chunk map concealing behaviors are effectively suppressed.

7.4.3. Impact of tolerance range

In our study, the modeling of peer departure is to mimic real behaviors of people. However, it is very difficult to get an empirical result which indicates how long the tolerance range of the peers could be. Longer tolerance range means the peers are patient, which might imply a higher tolerance degree towards strategic behaviors.

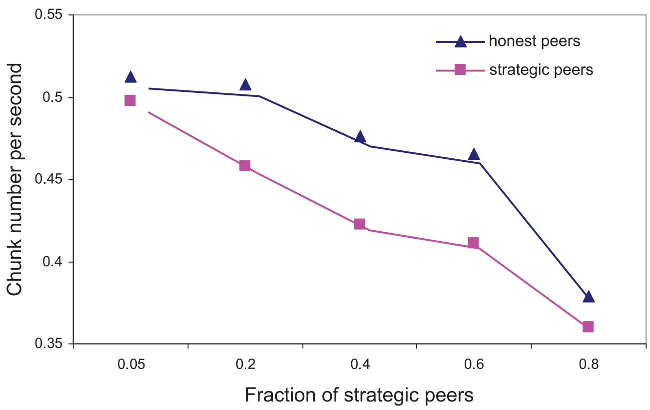


Fig. 22. Average download rate comparison.

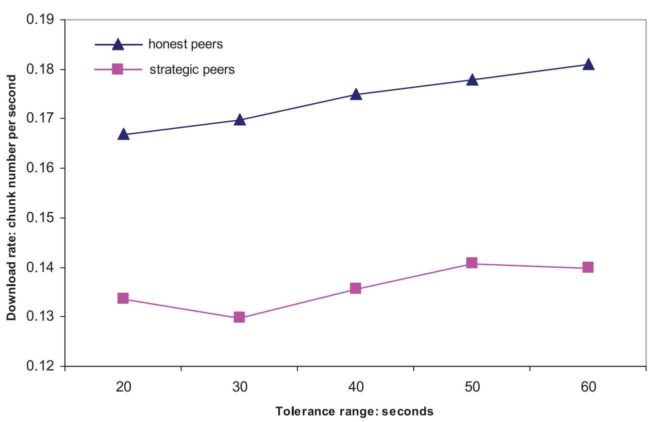


Fig. 23. Average download rate comparison.

To make sure the effectiveness of VBT in suppressing strategic behaviors, we further study whether VBT is still effective in punishing strategic peers when the tolerance range of the peers in the system varies. There are 20% peers set to be strategic peers. Fig. 23 confirms the effectiveness of VBT, by showing that when the tolerance range varies from 20 s to 1 min, the strategic peers are always punished by suffering from lower download rate than honest peers.

7.4.4. *Performance of rich peers*

The discussion in Section 2.3 implies that even after the value-based metric is enforced, rich peers still tend to behave strategically. To further investigate into this issue, we compare the performance of strategic rich peers and honest rich peers when the fraction of rich peers varies in the population. Only two categories of peers, high upload capacity (5000 Kbps, 10000 Kbps) and low upload capacity (384 Kbps, 1500 Kbps), are included in the system. We vary the fraction of high upload capacity peers in the system. 25 high upload capacity peers behave strategically, and the others behave honestly.

Fig. 24 shows that when the fraction of high upload capacity peers is small, below 10%, the strategic peers have higher average download rate than honest peers. However, when the fraction becomes larger, strategic peers suffer from lower average download rate than honest peers. A plausible explanation is that when the fraction of high upload capacity peers increases, the fraction of high upload capacity peers in rich peer's competitors also increases. Thus, it can no longer keep the unchoke opportunity at its neighbors simply by high upload rate.

Although when the fraction of rich peers is very small, they might tend to behave strategically. We believe that VBT is still very effective because 10% is considered as a small fraction. According to the

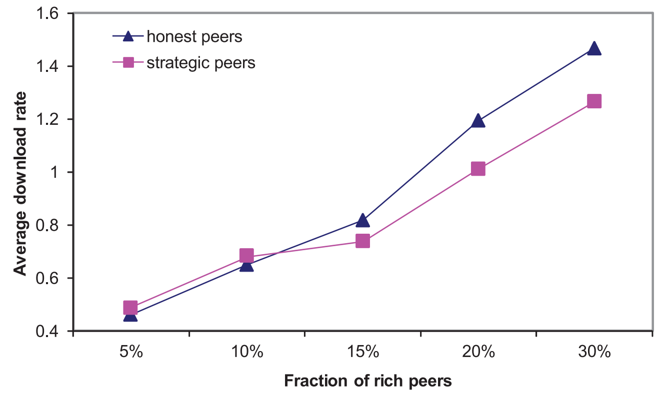


Fig. 24. Average download rate comparison.

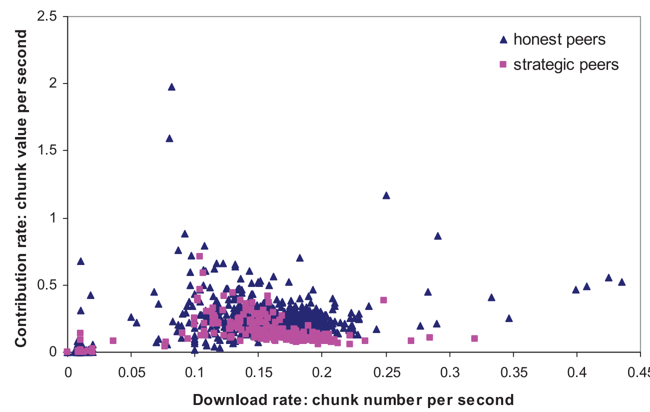


Fig. 25. Contribution rate and download rate in BitTorrent.

bandwidth distribution derived from the actual distribution of Gnutella nodes [11,12], the fraction of (5000 Kbps, 10000 Kbps) is 15%.

8. Devote more, gain more?

Under rate-based metrics, peers have no motivation to contribute high quality chunks to the system. When the value-based metric is carried out, is the goal of "*devote more, gain more*" really achieved? The experiment configuration in this section is the same with that of Section 5.3.

8.1. *Contribution rate and download rate*

In a P2P file-sharing system, one intuitive view is that you can obtain higher download rate if you devote more. Figs. 25 and 26 show the correlation between contribution rate and download rate for BitTorrent and VBT, respectively. From the perspective of the system, it will be more helpful to get high value chunks spread faster. Thus, we evaluate peers' contributions by the aggregated value of chunks.

In BitTorrent, as shown in Fig. 25, both for honest and strategic peers, higher contribution rate does not necessarily lead to higher download rate. While in VBT, the correlation is linear for honest peers, as shown in Fig. 26. Thus, in VBT, honest peers are encouraged to raise their contribution rates if they want to get higher download rate. However, strategic peers are treated totally differently. It is obvious to observe that even strategic peers have devoted very high contribution rates, the download rates they obtained do not increase. One possible reason is that strategic peers always tend to upload chunks with lowest values in their chunk maps to their neighbors. Thus, even if these peers saturate all their upload capacities, they still lose the unchoking opportunities from their neighbors.

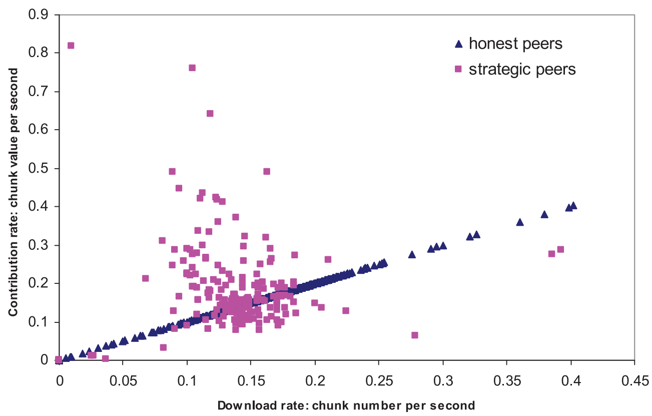


Fig. 26. Contribution rate and download rate in VBT.

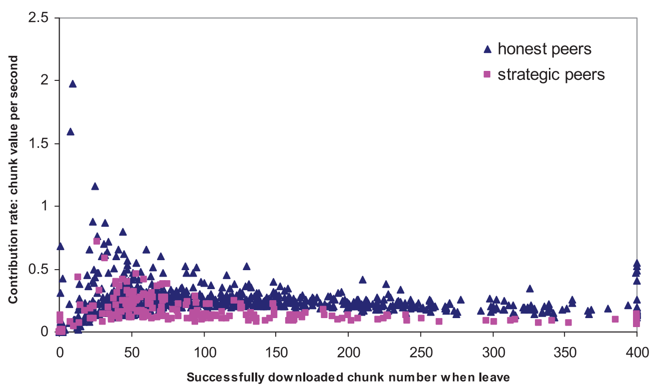


Fig. 27. Contribution rate and final result in BitTorrent.

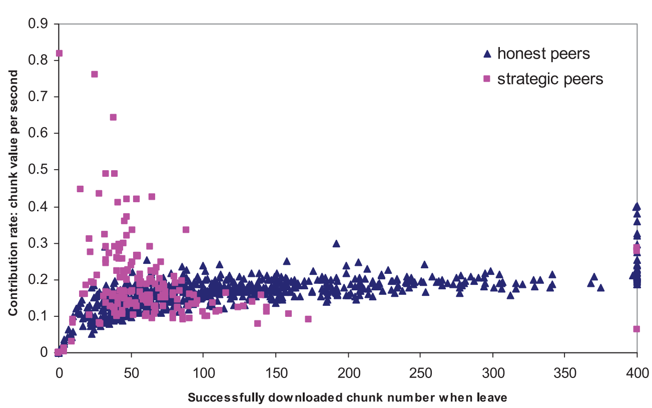


Fig. 28. Contribution rate and final result in VBT.

8.2. Contribution rate and long-term profit

If one peer keeps its upload rate as high as possible, will it actually benefit from this behavior in the long term? In other words, can it finally be successful in downloading the whole file? In a P2P file-sharing system, peers who honestly publish their chunk maps might quickly become unattractive to their neighbors, and be forced to quit from the system due to starvation as they have no chunks that attractive to the neighbors. Figs. 27 and 28 show the correlation between contribution rate and the *final result*, which is the chunk volume (i.e., number of chunks) successfully downloads when a peer leaves the system. We want to see whether or not higher upload rate will necessarily lead to good *final result*, which means, getting a larger fraction of the file instead of quitting at early stage because of starvation.

In BitTorrent, as shown in Fig. 27, honest peers and strategic peers encounter a similar situation. Peers who contribute higher rates cannot necessarily get to the late stage, and some peers who contribute very high rates (larger than 0.6) are starved at very early stage (under the volume of 100 chunks). In VBT, as shown in Fig. 28, there is a positive correlation between contribution rate and final result (the quit stage) for honest peers. However, the correlation is not linear. Only the peers who upload with high contribution rate can get to the late stage, meaning getting more chunks. However, for strategic peers, even they raise their contribution rates to very high levels, they are starved at an early stage.

In addition, the results of VBT also imply that after attaining a certain level, the contribution rate is not the bottleneck. There should be other bottlenecks which affect the final result. One possibility is the chunk map. Many peers might not have enough chunks to attract enough good neighbors.

9. Related works

In a P2P file-sharing system, each peer is encouraged to contribute more to the system, by the motivation of “devote more, gain more”, which is the fundamental principle of a P2P file-sharing system. Many research has been done on the investigation of the incentive schemes, to make the system more efficient and robust. In [13–15], a deterministic mechanism is carried out to enforce the law that each peer downloads as much as it uploads. The payment depends only on the contribution, and it seems precisely fair that everybody gets as much as it contributes. However, they neglect the difference among individual peers. Some rich peers who have large upload capacity would like to devote more than others to obtain a file if they can get faster download speed. Cohen [1] proposed a tit-for-tat policy in BitTorrent which reaps staggering success in P2P file-sharing systems. Levin et al., [6] proposed a proportional share mechanism to better fulfill the goal of “devote more, gain more”. Some research modified BitTorrent protocol for specific aims. Rahman et al., [16] uses effort-based incentive schemes instead of contribute-based incentive schemes to assist low privileged peers. Waheed et al., [2] modified BitTorrent’s optimistic unchoking policy by making low bandwidth peers try to unchoke peers who have similar bandwidth.

All the above incentive schemes try to make peers contribute more to the system. However, Jia et al., [17] argued that, oversupply is also a problem to the system. Many users are forced to seed extremely long time. They proposed several strategies to alleviate oversupply. Different from [18], we noticed that overpayment on each individual chunk is a culprit of inefficiency in P2P file-sharing systems. Thus, in this work, we investigate the phenomenon of overpayment and propose a value-based metric to alleviate overpayment in BitTorrent.

10. Conclusions

P2P systems have achieved outstanding success and much efforts has been put into investigating incentive mechanisms for strategic P2P networks. In this work, observing that different chunks have different values to both the system and individual peers, a value-based metric is devised to measure contributions instead of using rate-based metrics. A variation of BitTorrent is also proposed, called value-based BitTorrent (VBT). VBT is found to effectively punish the strategic behaviors of an under-reporting chunk map, and there is a positive correlation between investment and return for cooperative peers in VBT networks. Moreover, VBT always outperforms BitTorrent in terms of system performance. Taking the chunk value in the reciprocity process into consideration, the overpayment problem in a BitTorrent network is investigated, and four side effects of overpayment are identified. A new scheme is proposed to visualize overpayment and a series of metrics is proposed based on this method to quantify overpayment. The proposed VBT is found to be able to alleviate the degree of overpayment and consequently relieve the side effects of overpayment.

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