A Game Theoretic Approach to Provide Incentive and Service Differentiation in P2P Networks

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ABSTRACT

Traditional Peer-to-Peer (P2P) networks do not provide service differentiation and incentive for users. Consequently, users can easily access information without contributing any information or service to a P2P community. This leads to the "free-riding" problem and consequently, most of the information requests are directed toward a small number of P2P nodes which are willing to share information or to provide service, hence, the "tragedy of the commons" occurs. The aim of this work is to provide service differentiation based on the amount of services each node has provided to a P2P community. Since the differentiation is based on the amount of contribution, this encourages all nodes to share information/services in a P2P network. We first introduce a resource distribution mechanism for all information sharing nodes. This mechanism is a distributed algorithm which has a linear time complexity and guarantees the "Pareto-optimal" resource allocation. In addition, the mechanism not only distributes resources in a way to increase the aggregated utility of the whole network, but also provides incentive for other nodes in the P2P network to share information. Secondly, we model the whole resource request and distribution process as a competition game between all competing nodes. We show that this game has a Nash equilibrium and has a collusion-proof feature. To realize this game, we propose a protocol such that all competing nodes can interact with the information providing node such that the Nash equilibra can be reached efficiently and dynamically. Experiments are carried out to illustrate that the protocol provides service differentiation and induces incentive for nodes to share information or to provide service. Lastly, we show that our protocol is adaptive to different nodes arrival and departure events, as well as to different forms of network congestion.

1. INTRODUCTION

In the past few years, there have been tremendous interests on P2P networks. As witnessed by the traffic measurement of ISPs, a large percentage of traffic is due to P2P applications[2]. The emergence of P2P computing ensures users a new information exchange paradigm on the Internet, and this new paradigm has the potential to provide high information accessibility to large number of users.

Unlike the traditional client-server computing paradigm, P2P networks allow individual user (or node) to play the role of a server and a client at the same time. Therefore, nodes in a P2P network can help each other in file searching[1], file lookup[14, 15, 18, 20] as well as transferring information in an anonymous manner[6]. For the file searching process, the P2P networks evolve from a centralized file/directory lookup approach (e.g., Napster) to a distributed objects query approach (e.g., Gnutella). Since the distributed object query is a form of controlled flooding, new generation of P2P networks (e.g., Chord, CAN...etc) use the method of consistent hashing function to provide efficient file lookup service.

Although there has been significant progress in improving the performance of file searching/lookup in P2P networks, there exist some fundamental and challenging issues that remain unanswered. The *free-riding* and the *tragedy of the commons* are two of such problems. In [3], authors reported that nearly 70% of P2P users do not share any file in a P2P community and these users simply free-ride on other users who share information. Since there are few users who are willing to share information or to provide file transfer services, nearly 50% of all file search responses come from the top 1% of information sharing nodes. Therefore, nodes that share information and resources are prone to congestion, which leads to the tragedy of the commons problem [9]. In summary, the current P2P network does not provide *service differentiation*, so there is no *incentive* for users to share information or to provide file transfer services.

In this paper, we propose a protocol to provide service differentiation based on the contribution level of individual node. Roughly speaking, a node which shares popular files and provides more service (via file upload) to the P2P community will have a higher contribution level. In return, when this node asks for a file transfer service, it will receive higher utility than other competing nodes which have a lower contribution level. The incentive protocol we propose focuses on the file transfer process because the amount of data transfer per unit time is much higher than that of the object lookup/query. We address the importance of incorporating *incentive-compatible* resource distribution mechanism in a P2P protocol. The goals of the resource distribution mechanism are (i) to

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provide service differentiation, (ii) to encourage nodes to share information or services, (iii) to maximize the social welfare[16] or the aggregated utility of individual users. It is important to point out that our incentive protocol can be adopted by various P2P systems which use either the distributed query (e.g., Gnutella) or the consistent hashing approach (e.g., Chord or CAN).

Our incentive-compatible resource distribution mechanism has the following features:

1. *Fairness:* nodes which have contributed more to the P2P network should gain more resources or higher utility.
2. *Avoidance of resource wastage:* the mechanism will not assign more resource to a node that it cannot consume. In case there is a congestion between the communication path, the mechanism can adapt to the congestion level and distribute the appropriate amount of resource.
3. *Adaptability and Scalability:* the mechanism can adapt to conditions like network congestion and dynamic node joining or leaving. Since the mechanism is installed at each node, it is scalable as the size of the P2P network increases.
4. *Maximization of social utility*: Under certain circumstances, our mechanism not only maximizes the individual utilization, but achieves high aggregated utility for users as well.

As we will show, the proposed mechanism makes different requesting users to bid for resource and thereby creating a *dynamic competitive game*. In order to assure every nodes in the P2P network will follow the mechanism honestly, the dynamic game created should be *strategic-proof* and *collusion-proof.* The first property implies that following the proposed mechanism is the *best* strategy for each user in a P2P network. The second property implies that users cannot gain extra resource by cooperatively deceiving the system.

In here, we briefly present some related work. In [8], the authors address one possible mechanism for *centralized* P2P systems like Napster. Our work, on the other hand, can be applied to both centralized or distributed P2P networks. Zhong et al. [21] discuss shortcomings of *micro-payment* and reputation system. They propose a cheat-proof, credit-based mechanism for mobile ad-hoc networks. However, they did not address how to provide incentive and service differentiation. In [7], the authors discuss the economic behavior of P2P storage networks only. In [19], the authors model P2P networks as a Cournot Oligopoly game and give an elegant control-theoretical solution focusing on *global storage system* only. Our work, on the other hand, focuses on the file-transfer and bandwidth allocation of a P2P system and we use the mechanism design approach in designing a competitive game in a P2P system. Lastly, algorithmic mechanism design [12, 13, 17] provides a theoretical framework for designing incentive mechanisms.

The balance of our paper is as follows. In Section 2, we provide a general overview of the interaction between the information providing node and information seeking nodes. In Section 3, we present the resource distribution mechanism and its properties. In Section 4, we present the dynamic game model and how it can be applied to a P2P network. In Section 5, we present the performance evaluation of the proposed mechanism and competition game. Section 6 concludes.

2. INCENTIVE P2P SYSTEM OVERVIEW

In this section, we provide an overview of our incentive P2P system. In particular, we illustrate the interaction between different nodes during the file transfer process. In later sections, we will formally present the development of the resource distribution mechanism and its properties.

Similar to other P2P systems, each node in our incentive P2P network can play the role of a server and a client at the same time. During a file transfer process, the node which performs the file sharing service (e.g., uploading files to other nodes) is called the *"source node"*, which is denoted by $\mathcal{N}_s$. Nodes which request for file download from $\mathcal{N}_s$ are called the *"competing nodes"*, which are denoted as $\mathcal{N}_1, \mathcal{N}_2, \cdots, \mathcal{N}_N$, where N is the number of competing nodes. Each node in an incentive P2P network has a contribution value, which indicates how much service that node has provided to the whole P2P community. In order to maintain these values securely, there is an entity called the *"auditing authority"*, which is denoted as $\mathcal{A}$. One should view the auditing authority as a *distributed infrastructure*. In Section **??**, we will describe the implementation issues of $\mathcal{A}$.

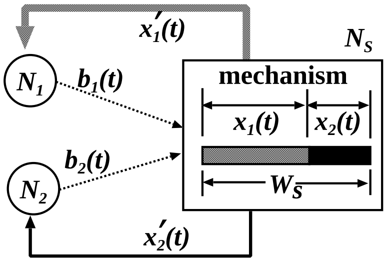

Figure 1: Illustrating two competing nodes and a source node.

Figure 1 illustrates a scenario where there are two competing nodes $\mathcal{N}_1$ and $\mathcal{N}_2$ which request file download service from the source node $\mathcal{N}_s$. The source node has an upload bandwidth resource of $\mathcal{W}_s$ (in unit of bps). From time to time, these competing nodes send messages $b_1(t)$ and $b_2(t)$ (in unit of bps) to $\mathcal{N}_s$, telling how much transfer bandwidth they want. Upon receiving these messages, $\mathcal{N}_s$ will use a resource distribution mechanism (to be presented in Section 3) to distribute its bandwidth resource $\mathcal{W}_s$ based on the values of $b_1(t)$, $b_2(t)$, as well as their contribution values which are denoted by $C_1(t)$ and $C_2(t)$ respectively. As a result, $\mathcal{N}_s$ sends information to $\mathcal{N}_1$ and $\mathcal{N}_2$ with bandwidth $x_1(t)$ and $x_2(t)$ respectively. However, it is possible that there is network congestion along the communication path between $\mathcal{N}_s$ to $\mathcal{N}_1$ (or $\mathcal{N}_2$), therefore, packets may be lost and the actual received bandwidth at node $\mathcal{N}_1$ and $\mathcal{N}_2$ are $x_1'(t) \leq x_1(t)$ and $x_2'(t) \leq x_2(t)$ respectively.

The auditing authority $\mathcal{A}$ in an incentive P2P network is a distributed database which carries two important functions. First, the auditing authority $\mathcal{A}$ will reply the contribution value of any node upon request, for example, the source node $\mathcal{N}_s$ needs to know the contribution values of its competing nodes so as to distribute its resource. Secondly, the auditing authority $\mathcal{A}$ maintains or increments the contribution value of a node, say $\mathcal{N}_s$, when $\mathcal{N}_s$ presents the *evidence* that it has performed some service for other nodes. As mentioned before, a source node will receive messages (e.g., b_i) from competing nodes and these can be used as evidence for contribution update. Figure 2 illustrates the two functionalities of $\mathcal{A}$. Again, we will discuss the implementation of $\mathcal{A}$, as well as issues on security and collusion in Section **??**.

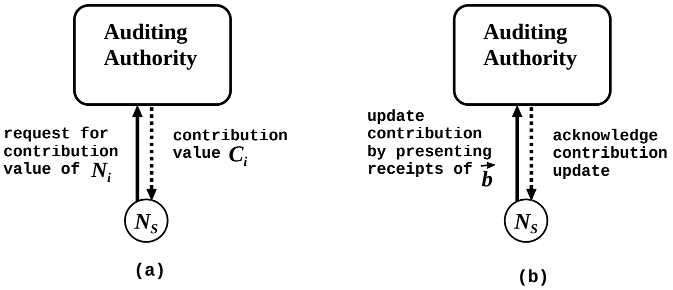

Figure 2: Illustration of functionalities of auditing authority: (a) reply contribution value upon request; (b) update contribution value upon request.

The message $b_i(t)$ plays two important roles. First, it can be regarded as the *"bandwidth bidding"* message from the perspective of the competing node $\mathcal{N}_i$. Another usage of $b_i(t)$ is that it is a *confirmation* to the source node $\mathcal{N}_s$ that $\mathcal{N}_i$ has received certain amount of service (measured in unit of bps). This kind of message helps the source node to determine the proper bandwidth assignment. If a competing node is inactive or failed, the source node will assume that the competing node cannot receive any data and therefore, it will not send any more packet to the competing node. The source node, on the other hand, can *adjust* the bandwidth resource assignment whenever it receives a bidding message. The justifications for this adjustment are: (1) a new arriving competing node may request $\mathcal{N}_s$ for a new file download; (2) an existing competing node finishes its file transfer service; (3) due to the network congestion situation, a competing node replies different values of bidding messages throughout the file download session. To efficiently utilize the bandwidth resource $\mathcal{W}_s$ and to improve the rate of contribution increase for $\mathcal{N}_s$, the source node needs to adjust bandwidth distribution among competing nodes.

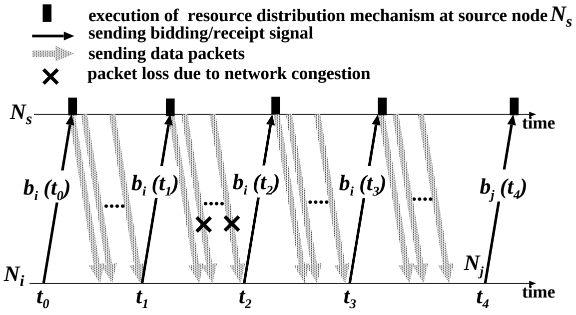

Figure 3: Interaction between competing nodes and a source node.

Figure 3 illustrates the interaction between the competing nodes and the source node $\mathcal{N}_s$. At time t_0, the competing node $\mathcal{N}_i$ requests for a file transfer of a large file F_i and sends a bidding message $b_i(t_0)$ to $\mathcal{N}_s$. After verifying the identity and contribution level of $\mathcal{N}_i$, $\mathcal{N}_s$ uses the resource distribution mechanism to determine the sending bandwidth $x_i(t_0)$, and delivers some data packets of F_i to $\mathcal{N}_i$ based on this rate allocation. After receiving these data packets, $\mathcal{N}_i$ sends another bidding/receipt $b_i(t_1)$ at time t_1, then $\mathcal{N}_s$ determines the the new resource allocation and sends some additional data packets of file F_i based on $x_i(t_1)$. Note that at this round of the data delivery, some data packets are lost due to network congestion, therefore, $\mathcal{N}_i$ sends a bidding/receipt $b_i(t_2)$ to $\mathcal{N}_s$ at time t_2, with $b_i(t_2) < b_i(t_3)$. The source node $\mathcal{N}_s$ adjusts the resource allocation and delivers additional data packets of file F_i to $\mathcal{N}_i$ at a lower rate. At time t_4, a new competing node $\mathcal{N}_j$ requests for a file transfer of the file F_j from $\mathcal{N}_s$ and it sends its bidding message $b_j(t_4)$, $\mathcal{N}_s$ adjusts the resource allocation based on the latest biddings of these two competing nodes $\mathcal{N}_i$ and $\mathcal{N}_j$.

3. RESOURCE DISTRIBUTION MECHANISM

In this section, we discuss how the source node, say $\mathcal{N}_s$, uses the mechanism to distribute its bandwidth resource $\mathcal{W}_s$ (in unit of bps) among all its competing nodes $\mathcal{N}_1, \ldots, \mathcal{N}_N$. For the ease of presentation, we start with some simple mechanisms and will elaborate on their shortcomings. Then we introduce some sophisticated features so as to provide service differentiation and incentive.

Even Sharing Mechanism (ESM): the first mechanism is to *evenly* divide the resource $\mathcal{W}_s$ among all competing nodes. When there are N competing nodes requesting for file downloads, $\mathcal{N}_s$ transmits a file to a competing node $\mathcal{N}_i$ with an assigned bandwidth x_i:

$$x_i = \frac{\mathcal{W}_s}{N} \text{ for } i = 1, \ldots, N. \tag{1}$$

Although this mechanism seems fair in distributing the resource, there are some inherent problems. First, the bandwidth resource wastage may be significant. The wastage can occur in at least two forms: (1) if the connection between $\mathcal{N}_s$ and a competing node is congested, then the assigned bandwidth is not fully utilized, (2) the physical download bandwidth of a competing node may be less than the assigned bandwidth of $\mathcal{W}_s/N$, so the source node $\mathcal{N}_s$ cannot deliver information at that rate. Note that resource wastage also implies that $\mathcal{N}_s$ contributes some service to the community, but the amount of work may not be counted toward its contribution. Another problem of this type of mechanism is that it provides no service differentiation among competing nodes. Therefore, rational users have no incentive to share information or service, consequently we have the tragedy of the commons.

Resource Bidding Mechanisms (RBM): the aim of this mechanism is to overcome the resource wastage problem mentioned above. Under this mechanism, every competing node is required to send a bidding message periodically to $\mathcal{N}_s$. Let $b_i(t)$ be the bidding message from the competing node $\mathcal{N}_i$ at time t and it indicates the *"maximum"* bandwidth (in unit of bps) that $\mathcal{N}_i$ can absorb at time t. Given all the bidding messages from competing nodes, $\mathcal{N}_s$ has the knowledge of the *upper bounds* bandwidth assignment and will not assign any bandwidth higher than $b_i(t)$ to $\mathcal{N}_i$ at time t. Note that one may think it is possible for some competing nodes to request for more bandwidth than they really need, we will discuss the rational bidding values of competing nodes in Section 4.

One important property of the RBM mechanism is that it provides the *max-min fairness*[4, 5]. Suppose $\vec{x} = [x_1, \ldots, x_N]$ is the bandwidth allocation for all N competing nodes with the feasible domain $x_i \in [0, b_i]$ for $i = 1, .., N$. Then a feasible allocation is max-min fair if and only if an increase of x_i within its domain of feasible allocation must be at the cost of a decrease of some x_j, where $x_j \leq x_i$. In other words, the max-min allocation gives the competing node with the smallest bidding value the largest feasible bandwidth while not wasting any resource for the source node $\mathcal{N}_s$. From [5], one can show that there exists a unique max-min fair allocation vector $\vec{x}$, and it can be obtained by the *"progressive filling algorithm"*. The algorithm initializes all $x_i = 0$, then will increase all competing nodes' bandwidth resource at the *same rate* of $1/N$, until one or several competing nodes hit their limits (i.e., $x_i = b_i$), then resource allocation for these competing nodes will not be increased any more. The algorithm will continue to increase the resource of other competing nodes at the same rate. The algorithm terminates when all competing nodes hit their limits, or the total resource $\mathcal{W}_s$ is fully utilized. Mathematically, we express the max-min resource distribution as follows. Let $\mathcal{N}_{\hat{1}}, .., \mathcal{N}_{\hat{N}}$ as N competing nodes sorted based on the non-decreasing value of b_i. The resource distribution of the RBM mechanism is

$$x_{\hat{k}} \quad = \quad \min\left\{ b_{\hat{k}}, \frac{\mathcal{W}_s - \sum_{i=1}^{\hat{k}-1} x_{\hat{i}}}{N - \hat{k} + 1} \right\} \qquad \hat{k} = 1, \ldots, N. \quad (2)$$

Figure 4(a) illustrates the RBM with four competing nodes of $\vec{b} = [1, 2.5, 2.5, 4]$ and the resource bandwidth $\mathcal{W}_s = 7$ Mbps. The resource allocation is $\vec{x} = [1, 2, 2, 2]$ (in unit of Mbps), which is depicted by the *"shaded region"* in the figure. Although the RBM avoids resource wastage, but it doesn't provide any *incentive* for nodes to share information. Two competing nodes with the same value of bidding will obtain the same amount of resource regardless of their actual contribution to the P2P community.

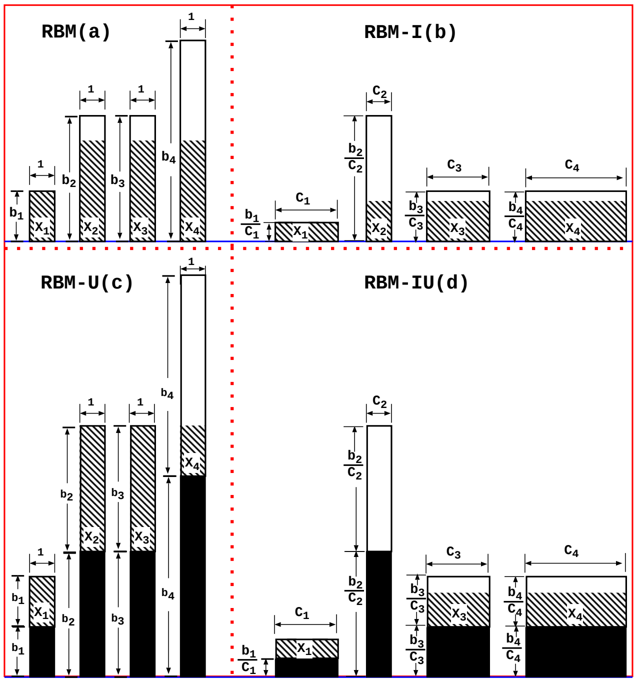

Figure 4: Resource distribution mechanisms: (a) RBM; (b) RBM-I; (c) RBM-U; (d) RBM-IU. The shaded region represents the amount of resource allocation for individual node.

Resource Bidding Mechanism with Incentive (RBM-I): To provide incentive, this mechanism takes the contribution level of competing nodes into account. Let C_i be the contribution value[1] of the competing nodes $\mathcal{N}_i$ and this value reflects the amount of work that $\mathcal{N}_i$ has performed, for example, sharing and uploading files for other nodes. The contribution value C_i can be retrieved from the auditing authority $\mathcal{A}$ at the beginning of the file transfer process, or every time when the source node receives the bidding message $b_i(t)$ from the competing node $\mathcal{N}_i$. One can enhance the resource bidding mechanism by enhancing the progressive filling algorithm as follows. We distribute resources to all competing nodes at the same time but with different rates. In particular, the competing node $\mathcal{N}_i$ will have a resource assignment rate of $C_i / \sum_{j=1}^{N} C_j$. Also, once the assigned resource to $\mathcal{N}_i$ reaches its limit of b_i, $\mathcal{N}_i$ will be taken out from the resource distribution. Therefore, one can view the mechanism as a weighted max-min resource distribution. Mathematically, we express the RBM-I as follows. Let $\mathcal{N}_{\hat{1}}, \ldots, \mathcal{N}_{\hat{N}}$ as N competing nodes sorted based on the non-decreasing value of b_i/C_i. The resource distribution is

$$x_{\hat{k}} \quad = \quad \min\left\{ b_{\hat{k}}, \frac{C_{\hat{k}} \left(\mathcal{W}_s - \sum_{i=1}^{\hat{k}-1} x_{\hat{i}} \right)}{\sum_{j=\hat{k}}^{N} C_j} \right\} \quad \hat{k} = 1, \ldots, N. (3)$$

Using the previous example in RBM but now with contributions $\vec{C} = [2.5, 1, 2.5, 4]$, the resource allocation is $\vec{x} = [1, 0.8, 2, 3.2]$ (in unit of Mbps), which is showed in Figure4(b). One important property of this mechanism is that if two competing nodes have the *same* bandwidth bidding values, then the assigned bandwidth will be *proportional* to their contribution values (i.e., $\mathcal{N}_2$ and $\mathcal{N}_3$).

Resource Bidding Mechanism with Utility Feature (RBM-U): The aim of this mechanism focuses on the efficiency of the resource allocation from the perspective of competing nodes' satisfaction. Consider a case of two competing nodes $\mathcal{N}_i$ and $\mathcal{N}_j$ which have the same contribution values. If the bandwidth resource at the source node is $\mathcal{W}_s = 1$ Mbps and the two bidding messages are $b_i(t) = 10$ Mbps and $b_j(t) = 1$ Mbps. Based on the RBM mechanism, they will each receive a bandwidth resource of 0.5 Mbps. Although the resource at $\mathcal{N}_s$ is efficiently utilized, but the degree of satisfactions of these two competing nodes are obviously different. To overcome this problem, we use the concept of *utility*[16] to represent the degree of satisfaction of a competing node given certain allocated bandwidth resource.

We first define the family of utility functions we consider in this paper. Given an allocated bandwidth x, the utility of the node $\mathcal{N}_i$ is denoted by $U_i(x)$. The utility function we consider in this work satisfies the following three assumptions: (a) $U_i(x)$ is concave (or the marginal utility $\frac{dU_i(x)}{dx}$ is non-increasing $\forall x \geq 0$), (b) $U_i(0) = 0$ and, (c) the utility depends on the ratio of $\frac{x}{b}$. In other words, $U_i(x_i) = U_j(x_j)$ whenever $\frac{x_i}{b_i} = \frac{x_j}{b_j}$ for any two competing nodes $\mathcal{N}_i$ and $\mathcal{N}_j$. The justifications for the above assumptions are as follows. First, the utility function is concave, which is often used to represent *elastic traffic* such as file transfer[16]. Concavity implies that the marginal utility is non-increasing as one increases the allocated bandwidth resource x. This captures the physical characteristics of elastic traffic: the utility increases significantly when a competing node starts receiving service. The increase of utility becomes less significant when the receiving bandwidth is nearly saturated. Second, the utility is zero when a competing node is not allocated any bandwidth. Third, because utility measures the satisfaction of a competing node, naturally, it is a function of the *fraction* of allocated resource over the bidding resource. Furthermore, this assumption normalizes the utility of all nodes so we can *compare* the degree of satisfaction of different nodes.

The objective of the RBM-U mechanism is to maximize the social

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[1] We will discuss how to update and maintain the integrity of contribution values of all nodes in Section **??**.

(or aggregated) utility. Formally, we have:

$$\max \sum_{i=1}^{N} U_i(x_i) \qquad \text{s.t.} \sum_{i=1}^{N} x_i \leq \mathcal{W}_s \quad \text{and} \quad x_i \in [0, b_i] \ \forall \ i.$$

It is important to point out that the implication of this maximization problem is to allocate resource to the competing node which currently has the *largest* marginal utility (i.e., largest $dU_i(x)/dx$). The allocation process starts with $x_i = 0$ for $i = 1, ..N$, then assigns resource to the node which has the largest marginal utility and ends when the resource $\mathcal{W}_s$ is used up, or all the competing nodes are fully satisfied with $x_i = b_i \forall i$.

Let us consider the following form of utility function which satisfies the above three assumptions:

$$U_i(x_i) = \log \left(\frac{x_i}{b_i} + 1 \right) \qquad \text{where } x_i \in [0, b_i].$$

The marginal utility is $U_i' = (x_i + b_i)^{-1}$. Therefore, the RBM-U mechanism tries to increase the resource to the competing node which has the smallest value of $x_i + b_i$ at any time. Using the previous example of RBM of 4 competing nodes with $\vec{b} = [1, 2.5, 2.5, 4]$ and $\mathcal{W}_s = 7$ Mbps, we use the above utility function and the resource allocation which maximizes the aggregated utility is $\vec{x} = [1, 2.5, 2.5, 1]$ (in unit of Mbps). This result is depicted in Figure 4(c). The figure shows graphically how the mechanism works. Each competing node, say $\mathcal{N}_i$, has a lower limit height which is equal to b_i (e.g., the darken region). The enhanced progressive filling algorithm distributes resource first to the competing node that has the *lowest* depth since that node has the *largest* marginal utility at that point. When the assigned resource to node $\mathcal{N}_i$ equals to its maximum bidding b_i, node $\mathcal{N}_i$ is taken out from the resource distribution. The algorithm terminates when all nodes reach their maximum allocation, or when the resource $\mathcal{W}_s$ is fully utilized.

Resource Bidding Mechanism with Incentive and Utility Feature (RBM-IU): One can view the RBM-IU mechanism as a *generalization* of the previous discussed mechanisms. This mechanism considers both the utilities of competing nodes and their contribution values. Each competing node, say $\mathcal{N}_i$, has its contribution value C_i and bidding message b_i. Mathematically, the RBM-IU is performing the following constraint optimization:

$$\max \sum_{i=1}^{N} C_i \log \left(\frac{x_i}{b_i} + 1 \right) \quad \text{s.t.} \sum_{i=1}^{N} x_i \leq \mathcal{W}_s, x_i \in [0, b_i] \ \forall \ i.$$

The RBM-IU mechanism enhances the progressive filling algorithm as follows: (a) We treat the competing node $\mathcal{N}_i$ as a bucket with area b_i and width C_i. (b) The bucket of the competing node $\mathcal{N}_i$ is located at the height b_i/C_i, therefore the upper limit of the bucket is at the height of $2b_i/C_i$. (c) At any time, the RBM-IU mechanism increases the amount of resource into the competing node's bucket which currently has the lowest height. In other words, the bucket that has the largest weighted marginal utility (i.e., weighted by the contribution value). It is interesting to observe that when competing nodes have the same contribution value, the RBM-IU is equivalent to the RBM-U mechanism. The spirit of this mechanism is to increase the amount of resource of the competing node which has the largest weighted marginal utility of $C_i/(b_i + x_i)$ with the rate of C_i. Figure 4(d) illustrates the RBM-IU mechanism with $\vec{b} = [1, 2.5, 2.5, 4]$, $\vec{C} = [2.5, 1, 2.5, 4]$ and $\mathcal{W}_s = 7$ Mbps. The final resource allocation is $\vec{x} = [1, 0, 2.3, 3.7]$ (in unit of Mbps). From the figure, one can observe that the mechanism fills the bucket of $\mathcal{N}_i$ at most up to its area limit of b_i with the resource distribution rate of C_i. The bucket of $\mathcal{N}_i$ at the "resource level" $(x_i + b_i)/C_i$ is guaranteed to have the marginal utility $C_i/(x_i + b_i)$. The algorithm terminates when all competing nodes reach their resource limit, or when the resource $\mathcal{W}_s$ is fully utilized.

The RBM-IU mechanism can be expressed by the following pseudo-code. The source node $\mathcal{N}_s$ maintains a sorted list of competing nodes with b_i/C_i in ascending order.

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RBM-IU Mechanism ()
1.  if ($\sum_{i=1}^{N} b_i \leq \mathcal{W}_s$) return $\vec{x} = \vec{b}$;/*no congestion*/
2.  l=2; u=1; /*upper and lower limits index*/
3.  v=$C_1$;   w=$\mathcal{W}_s$;   /* filling rate and resource
    capacity*/
4.  level = $\frac{b_1}{C_1}$;/*initialize resource level*/
5.  while (w> 0)
6.    if ( (min{$\frac{2b_u}{C_u}, \frac{b_l}{C_l}$} − level)*v≥w)
7.      level = level + w/v; w=0;
8.    else if ($\frac{2b_u}{C_u} < \frac{b_l}{C_l}$)
9.      w −= ($\frac{2b_u}{C_u}$− level)*v; level = $\frac{2b_u}{C_u}$; v −= $C_u$; u++;
10.   else
11.     w −= ($\frac{b_l}{C_l}$− level)*v; level = $\frac{b_l}{C_l}$; v += $C_l$; l++;
12. for (each i)
13.   $x_i = \min\{\max\{0, (\text{level} - \frac{b_i}{C_i}) * C_i\}, b_i\}$;
14. return $\vec{x}$;
```

From the above code, it performs the filling algorithm when the total bidding is greater than the total available resource. In determining the final "resource level", we have three cases in the *while* loop at line 5: (1) When the resource is used up, the loop ends with the final "resource level" (line 6-7). (2) If the next available resource level is at the upper limit (or bidding level) of some competing node, then we adjust the remaining amount of available resource and reduce the filling rate by that competing node's contribution value C_i since we won't give any more resource to that satisfied competing node (line 8-9). (3) If the next available resource level is a lower limit of some competing node, then we adjust the remaining amount of available resource and increase the filling rate by that competing node's contribution value C_i (line 11). The reason is this competing node will have the largest weighted marginal utility for its turn to gain the resource at a rate of C_i. Note that this is a *linear* algorithm with a complexity of $O(N)$ where N is the number of competing nodes at the source node $\mathcal{N}_s$. Therefore, resource distribution can be executed quickly.

Lastly, the following two important theorems state some of the *desirable* properties of the RBM-IU mechanism.

Theorem 1. *For any two competing nodes $\mathcal{N}_i, \mathcal{N}_j$, the mechanism RBM-UI assigns the bandwidth resources x_i and x_j such that:*

$$\text{if } \frac{C_i}{b_i} \geq \frac{C_j}{b_j} \Longrightarrow U_i(x_i) \geq U_j(x_j). \tag{4}$$

Proof: Please refer to [10].

Remarks: The implication of this theorem is that a client which has the highest contribution per unit resource request than any other clients will receive the highest utility. Therefore, the RBM-IU provides incentive to P2P system and it increases node's utility.

Theorem 2. *The resource allocation $\vec{x}$ is "Pareto optimal", which implies that the resource allocation vector cannot be improved further without reducing the utility of at least one competing node.*

Proof: Please refer to [10].

4. RESOURCE COMPETITION GAME

In our P2P network, each competing node sends bidding messages to the source node, in return, the source node uses the mechanism RBM-IU for bandwidth resource distribution. The *interaction* between the competing nodes and the source node can be described by the game theory framework[11]. We model the interaction of resource competition as a game and explore its solution and properties. Lastly, we discuss how this game can be incorporated into the P2P protocol such that it converges to the Nash equilibra.

4.1 Theoretical Competition Game

We model the resource bidding and distribution processes as a competition game among all the competing nodes. One basic postulate in the game theory is that the game structure is *common knowledge* to all players. In our competition game, we assume total amount of bandwidth resource $\mathcal{W}_s$ and all contribution values C_i's are common knowledge. This means that all nodes know the information, know that their rivals know the information, and know that their rivals know that they know the information, and so on. Also, we only consider the non-trivial situations when $\sum b_i > \mathcal{W}_s$. The competition game can be described as follows:

1. All the competing nodes are players of the game.
2. The bidding message b_i is the strategy of the competing node $\mathcal{N}_i$. A bidding vector $\vec{b} = \{b_1, b_2, ..., b_N\}$ is a strategy profile where N is the number of competing nodes in the game.
3. The mechanism RBM-IU defines the rules and the structure of the game. We can regard mechanism RBM_IU as a mapping function which has $\vec{C}$ and $\vec{b}$ as input parameters and returns $\vec{x}$ as output.
4. The outcome of the game is the vector $\vec{x}$ which represents the amount of bandwidth resource each competing node obtains.

Lemma 1. *The mapping function* RBM-IU*: $\vec{C} \times \vec{b} \rightarrow \vec{x}$ is quasi-concave in each individual's strategy b_i.*

Proof: Please refer to [10].

Theorem 3. *There exists at least one Nash equilibrium in the competition game.*

Proof: Please refer to [10].

Lemma 2. *For any player, say $\mathcal{N}_i$, the strategy $b_i^* = \frac{\mathcal{W}_s C_i}{\sum_{j=1}^N C_j}$ implies a resource allocation of $x_i^* = \frac{\mathcal{W}_s C_i}{\sum_{j=1}^N C_j}$ for $i = 1, \ldots, N$.*

Proof: Please refer to [10]. **Remark:** The implication of the above lemma is in guaranteeing that a player can gain its fair share of resource during the competition. For some players who have small contribution values, they will not suffer from resource starvation. But for free-riders, they will eventually gain zero resource in the competition.

Theorem 4. *The strategy profile $b_i^* = \frac{\mathcal{W}_s C_i}{\sum_{j=1}^N C_j}$ for player $\mathcal{N}_i$, where $i = 1, \ldots, N$, is a Nash equilibrium.*

Proof: Please refer to [10].

Theorem 5. *In the Nash equilibrium that $b_i^* = \mathcal{W}_s C_i / \sum_{j=1}^N C_j$ for player $\mathcal{N}_i$, $i = 1, \ldots, N$, the RBM-IU mechanism in the source node is collusion-proof.*

Proof: Please refer to [10].

4.2 Practical Competition Game Protocol

In the above sub-section, we show the interaction between the source node and all its competing nodes can be modeled as a competition game which has a Nash equilibrium solution. This solution assigns each competing node the amount of resource *proportional* to their contributions, efficiently utilizes all resource at the source node, and it also prevents collusion among group of competing nodes.

Although the theoretical competition game provides these attractive properties, there are gaps to fill so as to realize this theoretical competition game into an incentive P2P network. In particular, one needs to address the following problems:

P1 The information of contribution $\vec{C}$ and the amount of resource $\mathcal{W}_s$ is assumed to be common knowledge, how can this be implemented in a P2P system?

P2 In real life, a competing node, say $\mathcal{N}_i$, has its maximum download capacity, say w_i (in unit of bps). Also, due to the intermittent network congestion, the actual assigned bandwidth allocation x_i maybe less than the actual received bandwidth x_i'. These two factors will change the Nash equilibrium derived under the theoretical competitive game.

P3 In a dynamic environment like a P2P network, new competing node may arrive and request for file download, while existing competing node may leave due to the termination of its file transfer. Under these situations, how can the system reach the equilibrium point according to the change of the number of competing nodes.

To address these issues, let us first consider the behavior of the source node. Based on certain strategy profile $\vec{b}$ and contribution values $\vec{C}$, the source node carries out the RBM-IU for bandwidth resource distribution. The *justification* that the source node is willing to use this mechanism is that the allocation result is *Pareto optimal* (based on Theorem 2). This implies that following the RBM-IU mechanism, the source node can maximize its contribution value so it can enjoy better service for future file download request. But without perfect information for all competing nodes, the game solution may oscillate and induce resource wastage. In order for the source node to maximize its contribution, it has the *incentive* to help all competing nodes to reach the Nash equilibrium. In our practical game protocol, the source node will signal the competing node, say $\mathcal{N}_i$, the value of $S_i = \mathcal{W}_s C_i / \sum_{j=1}^N C_j$ when $\mathcal{N}_i$ initiates its request for file download. This information exchange is at low cost because: (1) the signal is sent only *once* for each competing node's arrival; (2) the signal value is computed on flight and it does not need global information of the contribution values of all nodes in a P2P networks. Therefore, the issue P1 is resolved.

For the behavior of the competing nodes, let us see how the signals sent by the source node may help the game to reach its equilibrium. Suppose that a competing node, say $\mathcal{N}_i$, has the maximum download capacity of w_i and a *signal variable* s_i. Initially, s_i stores the signal value sent by the source node, i.e., $s_i = S_i = \mathcal{W}_s C_i / \sum_{j=1}^{N} C_j$. The competing node $\mathcal{N}_i$ sends its initial bidding message $b_i = \min\{w_i, s_i\}$ to the source node. After each round of data transfer, $\mathcal{N}_i$ measures x_i', the amount of bandwidth resource it receives from the source node and stores it as the current signal value s_i, i.e., $s_i = x_i'$, To start the next round of data transfer, $\mathcal{N}_i$ sends a new bidding message $b_i = min\{w_i, s_i\}$ to the source node. This bidding strategy assumes that the source node uses the RBM-IU mechanism, so all competing nodes feedback their strategies so as to reach the Nash equilibrium. In the bidding message, competing nodes inform the source node (1) its download bandwidth limit, and (2) whether there is any congestion along the data transfer path.

The behavior of competing nodes described above is an attempt to resolve the issue of P2 and P3. However, one can show that using this protocol, the system may *not* be able to reach the Nash equilibrium. Consider the following illustrative example, initially the source node $\mathcal{N}_s$ has resource $\mathcal{W}_s = 6$ and it has one competing node $\mathcal{N}_1$ with $w_1 = 10$ and $C_1 = 1$. The source node sends $\mathcal{N}_1$ a signal of $S_1 = 6$, therefore, the initial bidding message from $\mathcal{N}_1$ is $b_1 = \min\{10, 6\} = 6$ and the resource allocation is $x_1 = 6$ (which is a Nash equilibrium point). Afterward, a new competing node $\mathcal{N}_2$ arrives with $w_2 = 1$ and $C_2 = 1$. The source node sends $\mathcal{N}_2$ a signal of $S_2 = 3$, therefore, the initial bidding message from $\mathcal{N}_2$ is $b_2 = \min\{1, 3\} = 1$. The final resource allocation is $\vec{x} = [5, 1]$ (which is also a Nash equilibrium point). Now a new competing node $\mathcal{N}_3$ arrives with $w_3 = 10$ and $C_3 = 1$. The source node sends $\mathcal{N}_3$ a signal of $S_3 = 2$, therefore, the initial bidding message from $\mathcal{N}_3$ is $b_3 = \min\{10, 2\} = 2$. The final resource allocation is $\vec{x} = [3, 1, 2]$. Note that this equilibrium point is *not* a Nash equilibrium since there is some degree of unfairness between the two homogeneous nodes $\mathcal{N}_1$ and $\mathcal{N}_3$, and $\mathcal{N}_3$ could have received a higher bandwidth if it increases its bidding. Another scenario which shows the final resource allocation is not a Nash equilibrium is that some of the competing nodes may suffer from the network congestion such that $x_i' < x_i$. When these nodes feedback their new biddings $b_i = x_i'$ for resource allocation, some resource at the source node will not be utilized and may remains idle. This condition continues even if these competing nodes are relieved from the congestion at a later time. In other words, they cannot gain back the amount of resource they could have obtained in the Nash equilibrium. In summary, each competing node needs to behave more *aggressively* in order to get the proper amount of resource and also help the system to reach the new Nash equilibrium efficiently.

To properly resolve issues P2 and P3, we propose the following extension protocol. Each competing node, say $\mathcal{N}_i$, enhances its bidding by sending

$$b_i = \min\{w_i, (1+\delta)s_i\} \tag{5}$$

where δ is a small positive constant for all competing nodes. The functionality of reporting a slightly larger bidding value is to explore the possibility of whether there is some idle resource at the source node. The Nash equilibrium result $\vec{x}^*$ in the theoretical model doesn't change except that the strategy profile is changed to be $\vec{b}^* = (1+\delta)\vec{x}^*$. In case there are idle resource or unfair allocation temporarily in the system, competing nodes which gain a smaller amount resource can increase their biddings and push the system to the new Nash equilibrium point. Therefore, their subsequent bidding values will increase. Eventually, a new equilibrium is made when each competing node bids $b_i = min\{w_i, (1+\delta)s_i\}$ and receives $x_i^{'} = s_i$.

From now on, we assume all competing nodes in the incentive P2P network send the bidding message according to Eq. (5). Obviously, all competing nodes interact with the source node will achieve a different allocation result in equilibrium as compared with the Nash equilibrium in the theoretical context. We classify these competing nodes into three categories at equilibrium. When the bidding is $b_i = w_i$ in equilibrium, physically the competing node receives $x_i' = w_i$, and the allocated resource must be $x_i = w_i$. It implies the competing node does not encounter any network congestion. When the bidding is $b_i = (1+\delta)x_i'$ in equilibrium, there are two cases to consider: (1) There is a bottleneck (with available bandwidth v_i) in between the competing node and the source node. Therefore, no matter how large the contribution value of the competing node or its bidding value, the competing node can only receive v_i amount of bandwidth resource. So we have $b_i = (1+\delta){x_i}' = (1+\delta)v_i$. (2) The competing node competes with other competing nodes for the resource at the source node, therefore, the bottleneck is on the source node side. So we know $b_i = (1+\delta){x_i}' = (1+\delta)x_i$. Suppose the above three categories of competing nodes in equilibrium are defined in the sets $\mathcal{N}_\alpha$, $\mathcal{N}_\beta$ and $\mathcal{N}_\gamma$ respectively.

Lemma 3. *At any equilibrium of the dynamics game, the following equality holds:*

$$x_i/C_i = x_j/C_j$$

for all $\mathcal{N}_i, \mathcal{N}_j \in \mathcal{N}_\gamma$.

Proof: Please refer to [10].

Lemma 4. *At any equilibrium of the dynamics game, the following inequality holds:*

$$x_i/C_i + \frac{1}{2}\delta x_i/C_i \geq x_j/C_j$$

for all $\mathcal{N}_i \in \mathcal{N}_\gamma$ *and* $\mathcal{N}_j \in \mathcal{N}_\alpha \cup \mathcal{N}_\beta$.

Proof: Please refer to [10].

Theorem 6. *The dynamic game equilibrium described above has the bandwidth allocation solution :*

$$x_i = \begin{cases} w_i & \text{if } x_i \in \mathcal{N}_\alpha \\ v_i & \text{if } x_i \in \mathcal{N}_\beta. \\ \dfrac{C_i}{\sum\limits_{j \in \mathcal{N}\gamma} C_j}(\mathcal{W}_s - \sum\limits_{j \in \mathcal{N}_\alpha} w_j - \sum\limits_{j \in \mathcal{N}_\beta} v_j) & \text{if } x_i \in \mathcal{N}_\gamma. \end{cases}$$

In addition, it becomes a Nash equilibrium solution when δ *approaches zero.*

Proof: Please refer to [10].

Remark: Although the equilibra in the dynamics game are not strictly Nash equilibra, they are close to Nash equilibra when δ is small. The allocation results from these equilibra are the same as the equilibrium allocation when $\delta = 0$. Therefore, we can regard the game reaching the Nash equilibra as if all player play the Nash's strategy profile.

5. EXPERIMENTS

In this section, we carry out experiments to illustrate the performance and the incentive property of resource bandwidth distribution, and show how our protocol can adapt to dynamic join/leave of competing nodes as well as network congestion.

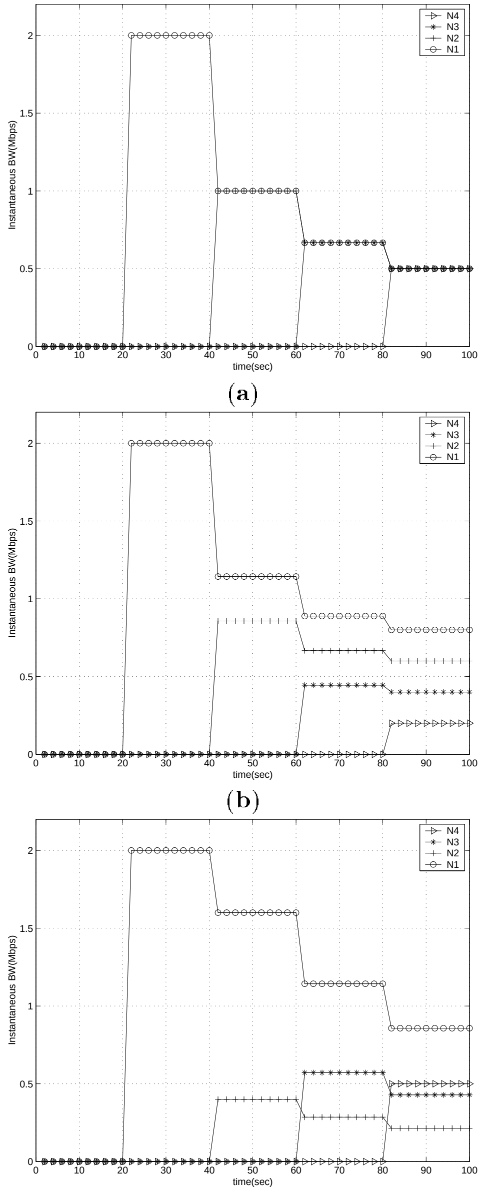
Experiment A (Incentive Resource Distribution): In this experiment, we consider a source node $\mathcal{N}_s$ with resource $\mathcal{W}_s = 2$ Mbps. There are four competing nodes $\mathcal{N}_1$ to $\mathcal{N}_4$ and their maximum download bandwidth is $\vec{w} = [2, 1.5, 1, 0.5]$ (in Mbps). The arrival times of $\mathcal{N}_1, \mathcal{N}_2, \mathcal{N}_3$ and $\mathcal{N}_4$ are at t =20, 40, 60 and 80 sec, respectively. Unless we state otherwise, there is a propagation delay of one second between a competing node and the source node $\mathcal{N}_s$. We consider three scenarios, each using different contribution values for these four competing nodes. In **Exp. A.1**, we have $\vec{C} = [100, 100, 100, 100]$, in **Exp. A.2**, we have $\vec{C} = [400, 300, 200, 100]$. And finally in **Exp. A.3**, we have $\vec{C} = [400, 100, 200, 300]$. Figure 5 illustrates the *instantaneous* bandwidth allocation for all competing nodes for $t \in [0, 100]$.

One can make the following observations.

- Figure 5(a) shows that when all nodes have the same contribution value, they will eventually get a *fair share* (or even distribution) of bandwidth resource. For example, for $t \in [20, 40]$, $\mathcal{N}_1$ gets all $\mathcal{W}_s$ resources of 2 Mbps since it is the only competing node and its $w_1 = 2$ Mbps. For $t \in [40, 60]$, the resource is evenly shared by $\mathcal{N}_1$ and $\mathcal{N}_2$ since they have the same contribution values. When all four competing nodes are present ($t \in [80, 100]$), each node will get a bandwidth resource $x = 0.5$ Mbps.
- Figure 5(b) shows that the bandwidth resource assignment is *proportional* to the contribution value of a competing node. When all four competing nodes are present ($t \in [80, 100]$), the resource allocation is $\vec{x} = [0.8, 0.6, 0.4, 0.2]$ (Mbps). Hence, the RBM-IU provides service differentiation, so nodes have incentive to share information and to provide service.
- Figure 5(c) shows that the protocol will not waste any resource at the source node. Given $\vec{C} = [400, 100, 200, 300]$, the resource distribution should be $\vec{x} = [0.8, 0.2, 0.4, 0.6]$ (Mbps). But since the maximum download bandwidth of $\mathcal{N}_4$ is $w_4 = 0.5$ Mbps only, the remaining resource (0.1 Mbps) will be distributed *proportionally* to $\mathcal{N}_1$, $\mathcal{N}_2$ and $\mathcal{N}_3$. The final resource distribution is $\vec{x} = [0.86, 0.21, 0.43, 0.5]$ (Mbps).

In summary, these experiments show that the RBM-IU can provide incentive service differentiation and will efficiently utilize the resource at the source node.

Experiment B (Adaptive to dynamic joining and leaving of competing nodes): In this experiment, we consider one source node $\mathcal{N}_s$ with resource $\mathcal{W}_s = 2$ Mbps. There are four competing nodes $\mathcal{N}_1$ to $\mathcal{N}_4$ with contribution $\vec{C} = [400, 300, 200, 100]$ and the maximum download bandwidth is $\vec{w} = [2, 1.5, 1, 0.5]$ (in Mbps). There is a propagation delay of one second between a competing node and the source node. We consider two scenarios of arrival and departure patterns: **Exp B.1:** $\mathcal{N}_1$ arrives and departs at $t = 40$ and $t = 160$, $\mathcal{N}_2$ arrives and departs at $t = 60$ and $t = 100$. $\mathcal{N}_3$ arrives and departs at $t = 80$ and $t = 120$ and $\mathcal{N}_4$ arrives and departs at $t = 20$ and $t = 140$. **Exp B.2:** $\mathcal{N}_1$ arrives and departs at $t = 20$ and $t = 100$, $\mathcal{N}_2$ arrives and departs at $t = 80$ and $t = 120$. $\mathcal{N}_3$ arrives and departs at $t = 60$ and $t = 140$ and $\mathcal{N}_4$ arrives and departs at $t = 40$ and $t = 160$. Figure 6 illustrates the instantaneous bandwidth allocation for time $t \in [0, 180]$.



(a)

(b)

(c)

Figure 5: Instantaneous bandwidth allocations: (a) $\vec{C} = [100, 100, 100, 100]$; (b) $\vec{C} = [400, 300, 200, 100]$; (c) $\vec{C} = [400, 100, 200, 300]$.

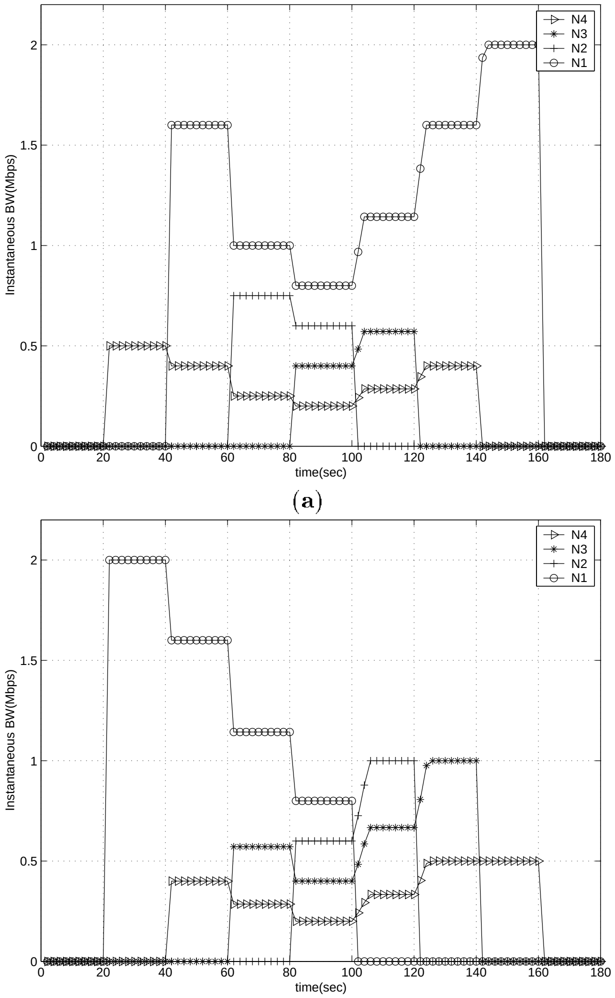
One can make the following observation:

- The protocol can assign the proper amount of resource to competing nodes without wastage. For example, for time $t \in [20, 40]$, Figure 6(a) shows that $\mathcal{N}_4$ obtains 0.5 Mbps (since this is its maximum download bandwidth). But for the same time period, Figure 6(b) shows that $\mathcal{N}_1$ can get 2.0 Mbps, its maximum download bandwidth and the full resource of the source node.

- Both Figure 6(a) and (b) show that the protocol fully utilize the resource of the source. For example, for period $t \in [40, 120]$, the source node distributes the resource proportionally to the contribution values of competing nodes. And the assignment is independent on the number of competing nodes and their arrival patterns.

- The protocol can reach the same equilibrium point, *independent* of the arrival and departure sequences of **Exp B.1** or **Exp B.2**. For example, consider the time period $t \in [80, 100]$. The resource distribution for both cases is $\vec{x} = [0.8, 0.6, 0.4, 0.2]$ (in Mbps), which is also the Nash equilibrium point.

In summary, these experiments show that the protocol is adaptive to the arrival and departure sequence, and it provides service differentiation to different competing nodes that have different contribution values.



(a)

(b)

Figure 6: Instantaneous bandwidth allocations for arrival and departure patterns (a) Exp B.1; (b) Exp B.2.

Experiment C (Adaptive to network congestion): In this experiment, we consider one source node $\mathcal{N}_s$ with resource $\mathcal{W}_s = 2$ Mbps. At time $t = 0$, there are already four competing nodes $\mathcal{N}_1$ to $\mathcal{N}_4$ in the system. These nodes have contribution values $\vec{C} = [400, 300, 200, 100]$ and maximum download bandwidth of $\vec{w} = [2, 1.5, 1, 0.5]$ (in Mbps). There is a propagation delay of one second from each competing node to the source node. In this experiment, we consider the dynamic congestion situation. In particular, the congestion occurs along the communication path $\mathcal{N}_1$ and the source node $\mathcal{N}_s$. Congestion occurs twice, at time $t = [30, 40]$ and at time $t = [50, 60]$. During the congestion, the available bandwidth along the communication path is reduced to 400 kbps.

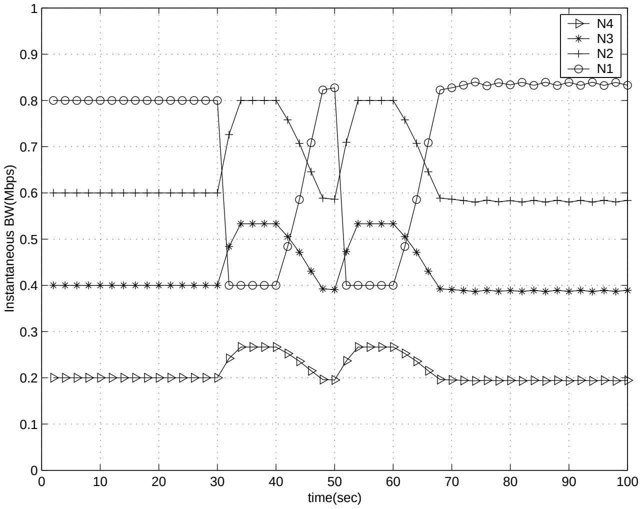


Figure 7: Instantaneous bandwidth allocations for four competing nodes, congestion occurs at $t = [30, 40]$ and $t = [50, 60]$.

Figure 7 illustrates the instantaneous bandwidth allocation of all four competing nodes for time $t \in [0, 100]$. One can make the following observation:

- At time $t = 0$, the system starts with a Nash equilibrium with resource allocation of $\vec{x} = [0.8, 0.6, 0.4, 0.2]$ (in Mbps).

- Between time $t \in [30, 40]$ (or $t = [50, 60]$), since there is a network congestion event, the competing node $\mathcal{N}_1$ receives less transfer bandwidth from the source node. Other competing nodes $\mathcal{N}_2$ to $\mathcal{N}_4$ can discover this idle bandwidth resource of 0.4 Mbps via their bidding messages. The source node $\mathcal{N}_s$ will distribute this excessive bandwidth resource *proportionally* to other three competing nodes based on their contribution values and a new Nash equilibrium will be reached (e.g., $t \in [35 - 40]$ and $t \in [55 - 60]$).

- When the congestion is released, the competing node $\mathcal{N}_1$ can gain back its proper resource of $x_1 = 0.8$ Mbps. Also, the Nash equilibrium can be quickly reached and the final resource allocation is $\vec{x} = [0.8, 0.6, 0.4, 0.2]$ Mbps.

In summary, this experiment shows that the protocol is adaptive to network congestion. During network congestion, the resource at the source node will not be wasted but rather distributed proportionally to other competing nodes.

6. CONCLUSION

In this paper, we present an protocol for P2P network so as to provide service differentiation and to induce incentive for nodes to share information or to provide service. The framework constitutes the resource allocation mechanism RBM-IU and the interaction protocol for competing nodes to reach equilibra of the competition game induced by RBM-IU. The efficiency of this framework is shown by the linear time algorithm to implement the RBM-IU, the simple feedback bidding messages for competing nodes, and the Pareto-optimality of RBM-IU allocation results. The robustness of this framework is shown by the equilibra of the competition game reached by all competing nodes. The justification for the source node to use this protocol is its guarantee of the Pareto optimality. On the other hand, competing nodes are willing to use the protocol because it guarantees the Nash equilibrium. We also show that the protocol is adaptive to various nodes arrival and departure events, as well as in different forms of network congestions.

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