An Auction Based Distribute Mechanism for P2P Adaptive Bandwidth Allocation

SUMMARY In P2P applications, networks are formed by devices belonging to independent users. Therefore, routing hotspots or routing congestions are typically created by an unanticipated new event that triggers an unanticipated surge of users to request streaming service from some particular nodes; and a challenging problem is how to provide incentive mechanisms to allocation bandwidth more fairly in order to avoid congestion and other short backs for P2P QoS. In this paper, we study P2P bandwidth game—the bandwidth allocation in P2P networks. Unlike previous works which focus either on routing or on forwarding, this paper investigates the game theoretic mechanism to incentivize node’s real bandwidth demands and propose novel method that avoid congestion proactively, that is, prior to a congestion event. More specifically, we define an incentive-compatible pricing vector explicitly and give theoretical proofs to demonstrate that our mechanism can provide incentives for nodes to tell the true bandwidth demand. In order to apply this mechanism to the P2P distribution applications, we evaluate our mechanism by NS-2 simulations. The simulation results show that the incentive pricing mechanism can distribute the bandwidth fairly and effectively and can also avoid the routing hotspot and congestion effectively.

key words: game theory, congestion pricing, credit incentives, hotspot avoidance, bandwidth allocation in P2P networks

1. Introduction

High-bandwidth data dissemination at the application layer has recently emerged as an important research topic, especially various P2P applications on overlay networks [1], [3]. The high bandwidth demand of the P2P distribution applications, e.g., P2P VoD, P2P file sharing, P2P live streaming [1]–[4] in the Internet poses a significant technical challenge in resolving the bandwidth allocation problem. Irregular bandwidth allocation is a prominent issue in the open network environment for P2P applications.

As nodes in P2P networks often reside at the edge of the Internet, they usually have limited upload and download capacities. Therefore, it is difficult to provide the bandwidth distribution service for the peak demand. As a result of this shortcoming, some serious traffic problems, such as link congestion, flash crowds and link overload, are aroused, which lead bad user experience or lower QoS of P2P applications. On the other hand, P2P networks make use of the attractive advantage that the application layer offers unprecedented flexibility and freedom to apply applications. Unfortunately, such freedom comes with challenges. One of the most important challenges is that each node is now an intelligent end host, rather than an obedient router; thus, cooperative behavior between nodes can no longer be assumed. Rather, each node may be selfish or dishonest in its actions. In microeconomic terminology, this means that each node will choose the action that maximizes its private utility. However, these selfish behaviors in P2P networks can cause not only uncooperative situation among nodes but network capacity loss.

How to overcome these bandwidth allocation problems mentioned above, researchers give some studies based on reactive approach [3]–[6] in which the allocation process starts after a hotspot or congestion is detected. However, it usually takes quite some time to retrieve duplicates of recently generated objects and it is difficult to provide good QoS provisioning for delay-sensitive P2P applications. And these mechanisms neglect the fact that nodes may deviate again from the protocol for selfish purposes that maximize their own profits, even if the deviant behaviors do harm to others, which will cause new congestion or new barricade in bandwidth allocation. In this paper, we design a rational bandwidth allocation mechanism based on auction mechanism, which makes the bandwidth can be allocated in accordance with the real needs of users, and ensure optimal social benefits for all users. Therefore, our auction based bandwidth allocation mechanism can mainly be used for fair bandwidth allocation in accordance with node’s real demand and overcoming node’s selfishness.

In our allocation mechanism, we give the assumption that a lot of selfish nodes are free to join the P2P network, and to share network bandwidth resources in internet. Because of their selfish characteristics, making them to maximize their own interests to enjoy network resources, always lying about the real needs of their network bandwidth. We consider that nodes can be divided into two parts: principal nodes (sellers) and agent nodes (buyers), which can also be regarded as source node and destination node in P2P network. The agent nodes have the demand of bandwidth by starting a P2P session, which can select one or more destination nodes for obtaining the audio/video or some other media objects. We assume that each of the nodes offers a dynamic and adaptive price as a bid for the bandwidth auction. The price for each node has a congestion-sensitive pricing factor and is proportional to the congestion level at the node.
The price is used as a bid for bandwidth auction by means of VCG (Vickrey-Clarke-Groves) mechanism.

In our allocation mechanism, the buyer node send their requirements (bids) to the seller nodes. Sellers allocate resources based on their bandwidth resources and the buyers’ requirements (i.e. their bids), then sellers calculate the payment of bandwidth and inform buyer node the price required to pay. Buyer nodes, who want to get the bandwidth resources, must evaluate payments and the value of his utility, and adjust bidding strategies in order to make utility optimal. All this above mentioned is one complete closed-loop transition of bid information, i.e., one process of bandwidth auction. In network bandwidth auction process, the shared bandwidth and the utility of buyers depend not only on their own bids in the auction, but on all other buyer’s bids in the auction. Therefore, there exist conflicts of interest between all nodes. This relationship constitutes a noncooperation game for sharing more bandwidth. Note that our mechanism for bandwidth allocation can converge to a Nash Equilibrium, i.e., any buyers can not improve their utility and bandwidth by changing unilateral bid.

This paper makes the following contributions: Firstly, we use the game theory method to investigate bandwidth allocation mechanism and the congestion avoiding technology in the P2P file distribution application. Based on the game model, we also propose a P2P Incentive-compatible Pricing Mechanism (PIPM) as a means to allocate the bandwidth in P2P application. Second, we give the proof on how PIPM can be used to pilot the traffic in P2P network to converge to Nash equilibrium. Third, in order to apply PIPM to the real P2P surroundings, we propose a novel algorithm based on VCG auction mechanism, which is a discrete stochastic learning algorithm and can be called VCG-based P2P Bandwidth Allocation Algorithm (VPBA in short). Under the guidance of the algorithm in simulations, nodes can converge to the optimal strategy through continuous learning, and the bandwidth allocation game will eventually converge to Nash Equilibrium.

The rest of this paper is organized as follows: we summarized the related works in Sect. 2. In Sect. 3, we formulated the PIPM, optimal objective of the bandwidth allocation mechanism and the properties of Nash Equilibrium in bandwidth allocation game. In Sect. 4, we gave VPBA for bandwidth allocation. Simulation and analysis were also specified in Sect. 4. Finally, we concluded the whole work in Sect. 5.

2. Related Works

Allocation of network bandwidth in P2P networks has been an active field of research over the past few years. Some of these works have been explicitly designed to support massive demand and avoid traffic congestion for P2P application by using game theory.

As an allocation mechanism, pricing mechanisms for QoS provisioning can be classified into static, dynamic, or auction-based schemes. In the case of dynamic pricing [7–10], the network adapts prices as the traffic load changes. In auction-based pricing schemes [11], users attach a bid to each packet indicating the willingness to pay for the delivery of the packet, and the network serves packets in descending order of their bids. Static pricing schemes [7] are simpler to implement compared with dynamic or auction-based schemes. However, this ease of implementation comes at a cost as prices have to be chosen a priori and it is not possible to react to changes in the users demand or traffic load in the network.

In [11], authors focus on free-riding problem in P2P application and provide auction based bandwidth-service differentiation scheme to incentive cooperate in a P2P network based on the amount of services each node has provided to the network community. Their Schema consists of the resource allocation mechanism RBM-IU (Resource Bidding Mechanism with Incentive and Utility Feature) and a network protocol for competing nodes to reach equilibria of the competition game induced by RBM-IU. Their contributions are: 1) RBM-IU can be implemented by a linear time algorithm; 2) the feedback bidding messages used by the competing nodes are simple; and 3) RBM-IU achieves Pareto-optimality allocation results.

In the case of multiple overlays, it is a challenging task to design an appropriate bandwidth allocation protocol, such that these overlays efficiently share the available upload bandwidth on peers, media content is efficiently distributed to achieve the required streaming rate, as well as the streaming costs are minimized. In [12], authors seek to design simple, effective and decentralized strategies to resolve conflicts among coexisting streaming overlays in their bandwidth competition, and combine such strategies with network coding based media distribution to achieve efficient multi-overlay streaming. Since such strategies of conflict are game theoretic in nature, authors characterize them as a decentralized collection of dynamic auction games, in which downstream peers bid for upload bandwidth at the upstream peers for the delivery of coded media blocks. With extensive theoretical analysis and performance evaluation, they show that these local games converge to an optimal topology for each overlay in realistic asynchronous environments.

Those literatures mentioned above is different from our schema, in that VCG mechanism is introduced into our schema for fair bandwidth allocation and more focus is given on avoiding routing congestion.

3. Allocation Mechanism for Bandwidth Allocation

3.1 Network Model

In this section, we will consider the basic network bandwidth allocation model as an auction for bandwidth in P2P multimedia file sharing system. The P2P multimedia file sharing system is required to encompass the key functions of object lookup, node-based aggregated traffic, and dynamic adaptations to network and node conditions. We model the bandwidth allocation problem as a non-cooperative game
with players whose strategies are sets of price for bidding bandwidth, with the background of P2P file sharing system. In the game, each node chooses a strategy that maximizes his utility and gets more bandwidth for getting multimedia files.

As far as file sharing system is concerned, every collaborative node in an application group is willing to transfer media flows to maximize the efficiency of a media session. Moreover, to achieve the load balance and avoid hotspots, each session may ship its flow by splitting its demand over the nodes of the same application group. Due to space limitation, we only describe the network model and do not cover the detail about multimedia distribution service.

Definition 1: Network model. A P2P network has a set \( N \) of nodes, where a node \( i \in N \) and there are \( L \) links in a P2P network, each node corresponds to a path, each path is composed by a set of links. Each link has a fixed capacity of \( C_l \) and \( l \in [1,2,3,\ldots,L] \). If node \( i \in L \), link \( f \) is located in the path of node \( i \). We assume that the path-link matrix \( A \) satisfies: if \( i \in l \), then \( A_{il} = 1 \); otherwise \( A_{il} = 0 \). Let vector \( C \) be total link capacity vector. All the links on the user’s rate can not be larger than the total link capacity, which satisfies \( AX \leq C \). The vector \( X \) represents all nodes share the network bandwidth.

Definition 2: Sessions and traffic demand. We consider the scenario that a set of sessions, \( S = \{ s_j | j = 1,2,\ldots,R \} \) share one Node Group \( V = \{ \omega | \omega \in V \} \) consisting of \( K \) nodes. Each session has a traffic throughput demand \( d_i > 0 \) over the links \( L \). Without loss of generality, we assume that \( d_1 > d_2 > \ldots > d_K \). The session ships its traffic flow by splitting its demand \( d_i \) over the group \( V \). A session is able to decide (at any time) how its demand is split among the nodes in the node group, i.e., a session decides what fraction of \( d_i \) should be relayed through each node in the group.

Let \( f_j^i \) denote the expected flow that the session \( j \) sends on the node \( i \in V \). Thus, the session \( j \) can fix any value for \( f_j^i \), as long as \( f_j^i \) satisfies the following: (1) nonnegative constraint: \( f_j^i \geq 0 \) and (2) demand constraint: \( d_1 = \sum_{l=1}^{K} f_l^i \).

Now, we turn our attention to a node \( i \in V \). Let \( c_i \) denote the bandwidth capacity of the node \( i \). Let \( f_i \) be the total flow on the node \( i \), i.e., \( f_i = \sum_{j=1}^{R} f_j^i \). And, \( f_i \) also denote the vector of all session flows on the node \( i \), i.e., \( f_i = (f_1^i, f_2^i, \ldots, f_R^i) \). The flow configuration \( f_i \) is the vector \( f_i = (f_1^i, f_2^i, \ldots, f_R^i) \). The system flow configuration \( f = (f_1, f_2, \ldots) \) is the vector of all session flow configurations and takes values in the strategy space \( F = \bigotimes_{k \in [K]} F_i \), where \( F_i \) denotes the set of all feasible \( f_i \); \( F \) denotes the set of all feasible \( f \) and \( \pi_i \in \Gamma, \Gamma \) means strategy space of node.

In this paper, we measure the performance of a node by a congestion function \( G(\cdot) \), which depends on the traffic configuration of all nodes. In the P2P session, node acts in a selfish manner and aims to find a strategy \( \pi \) that can maximize his node utility and maximize his bandwidth usage.

Since the congestion functions depend on the traffic configuration of all nodes, it turns out that the optimal decision of each node depends on the decisions made by other nodes. Due to the node being selfish, the allocation game is a non-cooperative game for bandwidth. Thus, we are interested in the Nash solution of the game. In other words, we seek a system traffic configuration such that no node finds it beneficial to change its decision on any node.

Consider a game of nodes and a set of strategy profile \( \Gamma \). A node \( i \) can play a strategy \( \tau_i \in \Gamma_i \) based on their utility function \( U_i(\tau_i, \tau_{-i}) \). \( \tau_i \) is the strategy space of node \( i \), \( \tau_{-i} \) and simply means the set of strategies chosen by all nodes except \( i \). The following definition formally defines the dominant strategy equilibrium.

The NE concept is of significant importance from a dynamic standpoint. In a practical scenario, a session changes its flow repeatedly in response to the varying load conditions of the nodes in the same application group.

3.2 P2P Incentive-Compatible Pricing Mechanism (PIPM)

Based on the network above, we will formulate our mechanism for bandwidth allocation.

In order to incentive the session to rationally tell his true demand for bandwidth and thus avoid the congestion, we assume that the price of a node is proportional to the level of congestion at the node. The level of service provided by the node \( i \) depends on the total flow offered to the node \( i \), i.e., \( d_i = \sum_{j=1}^{K} \omega_{ij} d_j \), and is quantified by means of a congestion function \( G_i(f) \). The higher \( G_i(f) \), the lower the level of service provided by the node. In this paper, \( G_i(f) \) is interpreted as the average delay on the node \( i \). We now present the congestion functions as follows:

\[
G_i(f) = \begin{cases} 
1/(c_i - d_i), & \text{if } f_i < c_i \\
\infty, & \text{if } f_i > c_i 
\end{cases} \tag{1}
\]

Correspondingly, the price for using the node \( i \) is a function of the total flow (i.e. total bandwidth demand) \( f_i \) carried by this node. Therefore, we define the pricing function as follows:

\[
\Omega_i(f_i) = \begin{cases} 
\omega_i(c_i - d_i) / f_i, & \text{if } f_i < c_i \\
\infty, & \text{if } f_i > c_i 
\end{cases} \tag{2}
\]

where the \( \omega_i \) can be interpreted as the congestion-sensitive factor of the node \( i \) and can be regarded as a weight factor. \( \omega_i \) determines the relative significance of the congestion level at the node \( i \). Similarly, the vector \( \omega = (\omega_1, \omega_2, \ldots, \omega_K) \) is the congestion-sensitive pricing vector.

We assume that node \( i \) receives a utility equal to \( U_i(f_i) \) if the allocated amount is \( f_i \); we assume that utility is measured in monetary units:

\[
U_i(f_i) = G_i(f_i) \times \Omega_i(f_i) = \omega_i(f_i - c_i) \tag{3}
\]

Property 1: \( U_i(f_i) \) is a continuous function, strictly increasing function of argument \( f_i \).

Property 2: \( U_i(f_i) \) is convex in \( f_i \).
Property 3: Wherever finite, \( f_i \) is continuously differentiable in \( U_i(f_i) \), we denote \( \kappa_i = \partial U_i / \partial f_i \).

For each node \( i \), over domain \( f_i \geq 0 \), the utility function \( U_i(f_i) \) is concave, strictly increasing, and continuous; and continuously differentiable.

Define auction strategy of node as price vector \( \omega = (\omega_1, \omega_2, \ldots, \omega_N) \), when each auction strategy \( \omega_i \) of node \( i \), \( \omega_i \in \omega \). \( \omega \) is the strategy space of node \( i \), \( \omega_{-i} \) and simply means the set of strategies chosen by all nodes except \( i \). The definition of node \( i \) true bid \( \omega_{T_i} \), it reflects the true extend of demand for network bandwidth according to node’s real network condition and ability. The definition of node \( i \) false bid \( \omega_{F_i} \), it reflects the false bid for network bandwidth.

The rules of allocation and payment for bandwidth in P2P Incentive-compatible Pricing Mechanism are as follows:

Bandwidth optimal objective:

\[
\begin{align*}
& \text{maximize } \sum_{i=1}^{N} U_i(x_i) \\
& \text{subject to } \sum_{i=1}^{N} A x_i \leq C \\
& \text{where: } x = (x_1, x_2, \ldots, x_i) \\
& i = 1, 2, \ldots, N \\
& x_i = f_i \geq 0
\end{align*}
\]

Payment:

\[
P_i = \max_{j=1,j \neq i} \sum_{j=1}^{N} v_j(x_j) - \sum_{j=1,j \neq i}^{N} v_j^-(x_j),
\]

where, \( v_j(x_j) \) can be interpreted as a valuation function on node \( v_j \). \( v_j(x_j) = \omega_{T_j} G(\hat{x}_j) \).

Utility function of node \( i \):

\[
U_i = \omega_{T_i} G(\hat{x}_i) - P_i = \omega_{F_i} G(\hat{x}_i) + \sum_{j=1,j \neq i}^{N} v_j(x_j) - \max_{i=1,j \neq i}^{N} v_j(x_i)
\]

The payment \( P \) means a credit incentive to be paid the node. Our PIPM mechanism’s goal is to incentivize each node to give a true bid, therefore, neither higher-reported bit nor lower-reported bit is able to increase the payment, and the node who reports his bid faithfully will get a payment as compensation not less than his consumption.

3.3 Properties of Equilibrium in the Mechanism

In this section, we investigate the properties of equilibrium imposed by PIPM. The existence question is answered in theorem 1. The optimal solution question is answered in theorem 2 and 3.

**Theorem 1.** In our bandwidth allocation mechanism, the congestion function and price function of each node is defined by (1) and (2), the existence of a Nash Equilibrium is guaranteed.

**Proof.** We define the point-to-set mapping \( f \in F \rightarrow \Xi(f) \subset F \), where \( \Xi(f) = \{ f_i \in F : f_i = \arg \max U_i \} \). \( \Xi \) is an upper semi-continuous mapping (according to the property 1). \( \Xi \) maps each point of the convex compact set \( F \) into a closed convex (according to property 2) subset of \( F \). According to the Kakutani fixed point theorem [13], there must exist a fixed point \( f \in \Xi(f) \), and such a point easily reaches a Nash Equilibrium.

**Theorem 2.** Given a vector of utility functions \( U \), a VCG mechanism chooses the allocation set \( x_i \in C \); there exists Nash Equilibrium, in such equilibrium that the elected set \( \hat{x} \) is an optimal solution to optimization problem (4).

**Proof.** The maximization in (4) is an optimal solution. The optimal solution is equivalent to the following Karush-Kuhn-Tucker (KKT) [14] conditions. For every \( f_i \in F \), there must exist a Lagrange multiplier \( \lambda_i \) such that, for every node \( i \in N \):

\[
\begin{align*}
K_i(f_i) &= \lambda_i, & \text{if } f_i > 0 \\
K_i(f_i) &\geq \lambda_i, & \text{if } f_i = 0
\end{align*}
\]

In other words, the KKT conditions are the necessary and sufficient conditions for a feasible bandwidth allocation to be a Nash Equilibrium.

**Remark.** As PIPM can reach Nash Equilibrium, according to definition of Nash Equilibrium, in such equilibrium that there exists \( U_i(\omega_{T_i}, \omega_{-i}) > U_i(\omega_{F_i}, \omega_{-i}) \), i.e., the utility when declaring true price \( \omega_{T_i} \) is not less than the utility when declaring false price \( \omega_{F_i} \). In other words, PIPM satisfies the incentive-compatible feature.

The proof of the remark can be deduced based on the formal definition of Nash Equilibrium, here we omit specification on the proof.

4. Algorithm and Experimental Evaluation

4.1 VCG-based P2P Bandwidth Allocation Algorithm (VPBA)

An incentive-compatible auction algorithm for bandwidth allocation based on the above mechanism will be discussed in this section. We will give specification on the algorithm. Finally, we present numerical results to illustrate the performance and the incentive property of our schema.

VCG based P2P bandwidth allocation algorithm is aimed to incentivize node to report their true bid for the fair bandwidth allocation so that the appropriate nodes with higher quality of service will be selected as a destination for applying the bandwidth, and therefore, the whole system’s performance and service ability can be improved. The network quality of P2P system and hot resource congestion are also much alleviated by our algorithm.

The main idea of algorithm can be concluded that \( U_{F_i} \) of node \( i \) with false bid \( \omega_{F_i} \) is not more than his \( U_{T_i} \) with true
bid \( \omega_i \), so that node \( i \) eventually takes the strategy of declaring true bid as his final choice. Specifically, we assume that all nodes involved in bandwidth allocation are selfish; and agent nodes bid for bandwidth of principal nodes in an auction. The price of bidding given by each agent node rely on \( G(\cdot) \), \( \omega \approx G(\cdot) \) and the higher the price of bidding is, the lower the network quality provided. In order to ensure the node provide true information as their bid, algorithm is ruled as follows: (i). Principal nodes flood the query packet for bandwidth auction. (ii). Agent node piggyback bid information to principal node in ack packet if he want to join the auction. (iii). Principal node will sort the bids from agent nodes in descending order, and select \( k, k \in N \) nodes in the front of queue as a set \( K \) of alternatives. Then, principal nodes will compute out the valuation, payment and utility of agent nodes according to agents’ piggybacked bids , and return those items back to agent nods. Agent node will compare all those items for making his utility incensement. If there is no incensement, agent node will change his bid in next round for getting bandwidth. (iv). With several bidding rounds eclipsed, principal node select \( k \) nodes in the descending order \( K \), and declare the \( k \) candidate node as bandwidth placement destinations. (v). The agent node finally pays for an amount of \( p_i \) to principal nodes, and after receiving the payment the principals open his spare queue tunnels to send P2P packets to those placement nodes.

We can conclude from the rules that agent higher or lower bidding price would not make his utility incensement; since if there is higher price, the agent will pay for more “money” than true price, if there is lower price, agent node will be kick out from the alternative queue.

Algorithm 1 VCG-based P2P Bandwidth Allocation Algorithm (VPBA)

\[
\begin{align*}
\textbf{Require:} & \text{ Given a random principal node proclaiming bandwidth auction } \, \Omega (\omega_1, \omega_2, \ldots, \omega_k) \, \text{ in principal node, such that } \Omega_{\text{init}} = (0, \ldots, 0); \\
\textbf{for} (i = 1; i \leq k; i++) \, \textbf{do} & \\
1: & \text{ node } i \text{ sends } \omega_i \text{ to principal node} \\
2: & \text{ principal node replaces } \omega_i \text{ in } \Omega_{\text{init}} = (0, \ldots, 0) \\
3: & \textbf{repeat} \\
4: & \text{ sort } \Omega(\omega_1, \omega_2, \ldots, \omega_k) \text{ in ascending order} \\
5: & \text{ select } k \text{ nodes in the front of } \Omega \text{ to set } K \\
6: & \text{ compute } p_i \text{ and } u_i \text{ then send them to node } i \\
7: & \text{ node } i \text{ put } U_i \text{ and } v_i \text{ into } \text{utility}[] \text{ and bid}[] \text{ respectively} \\
8: & \text{ If node } i \text{ lie } \omega_i = \omega_i \pm x \\
9: & \text{ principal node revise } \omega_i \text{'s value accordingly in } \Omega \\
10: & \textbf{until } \omega_i > 0 \\
11: & \text{ If } U_{\text{fj}} \leq U_{\text{fj}}(\omega_i) \\
12: & \text{ Then node } i \text{ finally sent his true bid } \omega_i \\
13: & \textbf{end for} \\
14: & \text{ principal node chooses } k \text{ nodes from alternative queue as bandwidth placement destination and agent nodes pay for } p_i \text{ as payment for bandwidth. }
\end{align*}
\]

Assumption 1: The nodes participating in the allocation mechanism are rational, and they are sensitive to all incentive items which will can make their utility improvement and make them get bandwidth. As false bid can not bring the improvement in the utility of node, the node is not necessary to lie in order to reduce the risk of making a false report.

The \( \omega_i \) is inversely related to the performance of the node, and can be normalized to the value subject to \( 0 \leq \omega_i \leq 100 \). We initialize \( (\omega_1 = 0, \omega_2 = 0, \ldots, \omega_k = 0) \in \Omega \), which means every node is not chosen as the bandwidth destination in the beginning stage. The principal nodes give a periodical bandwidth request broadcast at every 2second, and the refreshing period of bids, valuations and utilities of agent nodes is 400millisecond, and one auction period time is 4second.

4.2 Simulation Methodology

We have conducted simulation experiments to evaluate our proposed distributed algorithm in a P2P overlay network, using packet-level event-based simulation scenarios by NS2.

Network: The basic network topology is a Euclidean space model. We apply our P2P bandwidth allocation algorithm in the 2D-Euclidean space. Each node in homogeneous environment has a set of neighbors with which it communicates by message passing. Links are directed. Traffic can however flow in both directions on the links. We consider a P2P network made of total 1000 nodes and links. Each link has 2 mBps capacity in both directions. Connections between nodes is established by standard TCP.

Application: Our implementations are based on a P2P file sharing system, and all simulations are carried on NS-2, where nodes are organized in an overlay network.

Metrics: System average delay, the number of hot spots, throughput, packet loss ratio, adaptation of Join/Leave nodes, effectiveness of incentive bandwidth resource distribution and effectiveness of incentive-compatible are chosen as metrics for evaluating our algorithm VPBA. The efficiency and quality of service in P2P file system can be evaluated by delay and throughput. For each experiment, we run the simulation multiple times and the variance in results from multiple rounds is just low, always < 10%.

- Adaption of Join/Leave Nodes. We consider this metric as a flexibility of our mechanism in dynamic surroundings of nodes. This metrics can be reflected that the bandwidth allocation is independent of the number of competing nodes and their arrival patterns.
- Effectiveness of incentive-compatible: Effectiveness of incentive-compatible for our algorithm can be considered that one node chooses the true bid will be the dominant strategy in order to get more utility and the other false bid values will be disposed. Node’s strategy probability means the probability of a strategy adopted by one node. It can be used to evaluate the incentive-compatible feature of our VPBA.
- Effectiveness of Incentive Bandwidth Resource Distribution: This metric can be used to evaluate the incentive feature of our mechanism, i.e., the bandwidth assignment is proportional to the real price value of a
Average delay: Average delay represents the average access time, when files are replicated between the requestor node and the source node. We assume a virtual time to reflect the performance perceived by the end node where the time may be Round Trip Time (RTT), hops, or even certain economic cost of the path between two nodes. Here, we choose RTT as the metric in our simulation.

Hotspots: In our simulation, the hotspots (threshold > 500ms) are affected by both the amount of nodes and packet loss ratio in the network link between bandwidth requestor and provider.

4.3 Simulation Results

4.3.1 Adaption of Join/Leave Nodes

There are four agent nodes to with bids [23, 12, 56, 34] and every node has the download bandwidth of 2Mb/s. We consider two scenarios of arrival and departure patterns:

Case(1) node 1 arrives and departs at t=2min and t=14min; node 2 arrives and departs at t=8min and t=12min; node 3 arrives and departs at t=6min and t=12min; node 4 arrives and departs at t=4min and t=14min. Figure 1 (a) illustrates the instantaneous bandwidth allocation in case(1).

Case(2) node 1 arrives and departs at t=4min and t=14min, node 2 arrives and departs at t=8min and t=12min, node 3 arrives and departs at t=6min and t=14min, and node 4 arrives and departs at t=2min and t=10min. Figure 1 (b) illustrates the instantaneous bandwidth allocation in case(2).

We can make the following observations: The VPBA can assign the proper amount of bandwidth resource proportionally to the bid values to agent nodes without wastage. For example, for period t=(2min-4min), Fig. 1 (a) shows that node 1 obtains 0.5Mb/s. But for the same time period, Fig. 1 (b) shows that node 4 can get 2.0Mb/s, its maximum download bandwidth and the full resource of the source node. Both Fig. 1 (a) and (b) show that the VPBA can fully utilize the bandwidth resources. For another example, for period t=(4min-12min), the source node distributes the bandwidth resource proportionally to the bid values of the agent nodes. The assignment is independent of the number of agent nodes and their arrival patterns. Figure 1 of instantaneous bandwidth allocations for arrival and departure patterns case(1) and case(2) shows that the VPBA allocates the bandwidth proportionally to the bid values of the agent nodes. The assignment is independent of the number of agent nodes and their arrival patterns.

In summary, these examples show that the VPBA is adaptive to the arrival and departure sequence, and it provides service differentiation to different competing nodes having different bid values.

4.3.2 Effectiveness of Incentive Bandwidth Resource Distribution

We consider there are 4 competing nodes to bid for bandwidth in VPBA. The download bandwidth of every link is 2Mb/s. Their bids are 4, 16, 35, and 22 respectively. We consider the scenario, where each node is using different bid for competing bandwidth. We have Fig. 2 illustrates the
bandwidth allocation for all the competing nodes. One can make the following observations: Figure 2 shows that the bandwidth assignment is proportional to the bid value of a competing node. When all four competing nodes are present in the period t=(65s-80s), the bandwidth allocation vector is $[0.85, 0.45, 0.35, 0.25]$ (Mb/s). Hence, VPBA provides service differentiation, such that nodes have incentive to share information and to provide services.

Figure 2 also shows that the VPBA will not waste any resource at the source node. When time comes 65s, the bandwidth allocation vector of all four competing nodes is $[0.85, 0.45, 0.35, 0.25]$ (Mb/s) and the total bandwidth is 1.9Mb/s. Since the maximum download bandwidth of is 2Mb/s, the remaining resource (0.1Mb/s) will be distributed proportionally to the four nodes. The final bandwidth distribution is $[0.875, 0.475, 0.375, 0.275]$ (Mb/s) after t=80s.

In summary, these examples show that the VPBA can provide incentive service differentiation and will efficiently utilize resources at the source node.

4.3.3 Effectiveness of Incentive-Compatible Feature for VPBA

This set of experiments to verify that every node in VPBA declare true bid as his dominant strategy in order to increase node’s utility, i.e., there is no motive for node to lie in the bandwidth allocation auction. Let $\omega_i$ be node $i$’s bid strategy set, and bid value is respectively $(7, 49, 33, 15)$, where 15 is node’s true bid. Let be $\omega_j$ node $j$’s bid strategy set, and bid value is respectively $(11, 12, 26, 53)$, where 12 is node’s true bid. In order to evaluate effectiveness of incentive-compatible of our proposed algorithm, both cases are compared in the situation where node uses dominant strategy and other strategies for bidding on bandwidth allocation.

We take 1000 nodes in this scenario, and the total run time is 300 rounds, here, one round is defined as the complete time of total agent nodes achieving to get a copy of bandwidth. Without loss of generality, node $i$ and $j$ are chosen randomly from the agent nodes and the initial probability of nodes are subject to uniformly distribution, i.e., $P(\omega_i) \sim U(x) = 1/(b-a), a \leq x \leq b$.

Figure 3 shows the relationship between the change of probability of node’s bid strategy and the number of iteration rounds of VPBA. As shown in Fig. 3 (a), node $i$’s bid strategy set is $(7, 49, 33$ and $15$), where 15 is node $j$’s true bid; and with the iteration rounds gone, the probability of bid value 15 has gradually converged to 100%, i.e., choosing the true bid value as node’s bid strategy is a dominant strategy under the VPBA. It is because the node $i$ choose a value randomly in the set of $(7, 49, 33, 15)$ as his bid for getting bandwidth at the beginning rounds of iteration, however node $i$ find he will get more utility only by choosing true bid value as his strategy in the auction; therefore, choosing the true bid will be the dominant strategy in order to get more utility and the other false bid values will be disposed. One can also make the observation that similar result appears in Fig. 3 (b).

Both results in Fig. 3 (a) and 3(b) not only show that VPBA is an algorithm with incentive compatibility, where the nodes can get more utility only by declaring true bid, therefore selfish or dishonest application for bandwidth can be restrained and bandwidth can be allocated fairly; but also show VPBA is able to guide the node to converge to dominant strategy through continuous learning, and the whole P2P system will converge to a stable Nash Equilibrium.

4.3.4 Comparison of Average Latency

Additional, in order to evaluate the application performance, especially the network quality of P2P system in our proposed P2P Incentive-compatible Pricing Mechanism and VPBA, we compare the metrics of network quality in P2P file sharing system with our mechanism against the metrics of network quality in the system with other three mechanisms. The three mechanisms are listed as follows:

- Shortest Path (SP) Strategy [15]: With this strategy, a node selects a parent from the candidates that make the accumulated service latency the smallest. In SP strategy, the nodes randomly choose their parents in a best-effort manner, which may result in a high tree since a large number of nodes may compete for a single well located node, making the subtree under the target node grew very tall.

- CODIO mechanism [14]: It introduces the concept of congestion-distortion optimized (CODIO) packet scheduling. The mechanism pilots P2P streams at the source node and varies the rate of streams when the high traffic happens.

- No mechanism: It represents the case when no bandwidth allocation mechanism is running

There are total 1000 nodes in this simulation scenario. As shown in Fig. 4, the average system delay of No mechanism is growing fastest, and the average delay of our mechanism outperforms the other three mechanisms by varying the number of node from 1 to 1000. The latency in our proposed
mechanism is 6–10 percent less than that of the mechanism CODiO and SP, and 25 percent less than the case when no mechanism is done. When nodes is 800, the latency of our mechanism is 260 ms, whereas other mechanisms reach 290 ms at least. This example shows that our mechanism is better than other mechanisms in the latency.

In summary, results in Fig. 4 can show that the system delay in our mechanism is smallest of four schemes in simulations; it is mainly because our VPBA is more adaptive to network congestion. During network congestion, the bandwidth at the source node will not be wasted but rather distributed proportionally to the most appropriate competing node selected by auction of bandwidth allocation.

4.3.5 Avoidance of Hotspot Congestion

In this scenario, we use the number of hotspots to study the performance of four mechanisms. In simulation, the hotspots are affected by both the amount of nodes and packet loss ratio in the network link between bandwidth requestor and provider.

We firstly consider the number of hotspots by fixing packet loss ratio=0.0004 and varying the nodes from 400 to 1000. Figure 5(a) shows the hot node congestion (congestion threshold> 500ms) of four mechanisms. Generally, the increase of nodes will in turn increase the hotspots when all four mechanisms are applied. From Fig. 5(a), we can make the observation that the number of hotspots in our mechanism, SP, CODiO, and no mechanism are 71, 78, 84, and 102, respectively, when nodes are increased to 1000. There is a better improvement for avoiding hotspot congestion, if our mechanism is applied.

Then, we fix the number of nodes as 1000 and vary the average packet loss ratio. The results also imply that for P2P system with our mechanism, the avoidance for hotspot congestion is still good at the peak of packet loss ratio. As shown in Fig. 5(b), hotspots in all mechanisms increase as the packet loss ratio increases. However, our mechanism always performs the best in all four mechanisms.

5. Conclusion

We have developed a game theoretic methodology to investigate the P2P bandwidth allocation problem in multisource P2P multimedia file sharing applications by means of appropriate bidding mechanism. Assuming that the bandwidth allocated to any node is proportional to the node’s congestion level and node’s running ability, we showed that the nodes can always be allocated proper amount bandwidth according to his pricing under our mechanism. We investigated what utility function is needed to elicit truthful revelation of node real running ability and how it can be efficiently computed by our VPBA algorithm based on the P2P Incentive-compatible Pricing Mechanism. To illustrate the correctness and effectiveness of our mechanism and our algorithm, we give formal proof on incentive-compatible feature and existence of NE. Furthermore, simulations are shown that the quality of network in P2P system has been distinctly improved by our mechanism.
References

[1] S. Eum, S. Arakawa, and M. Murata, “Self organizing topology transformation for Peer-To-Peer (P2P) networks,” IEICE Trans. Commun., vol.E93.B, no.3, pp.516–524, March 2010.

[2] Y. Inoue, S. Sugawara, and Y. Ishibashi, “Efficient content replication strategy for data sharing considering storage capacity restriction in hybrid Peer-to-Peer networks,” IEICE Trans. Commun., vol.E94.B, no.2, pp.455–465, Feb. 2011.

[3] Z. Xiang et al., “Node-to-node based multimedia distribution service,” IEEE Trans. Multimedia, vol.6, pp.343–355, April 2004.

[4] A. Mavlankar, J. Noh, P. Baccichet, and B. Girod, “Optimal server bandwidth allocation for streaming multiple streams via P2P multicast,” IEEE J. Sel. Areas Commun., vol.22, pp.121–133, Jan. 2004.

[5] R. Kumar, Y. Liu, and K. Ross, “Stochastic fluid theory for P2P streaming systems,” Proc. IEEE INFOCOM, pp.919–927, Anchorage, AK, 2007.

[6] C. Wu, B. Li, and S. Zhao, “Multi-channel live P2P streaming: Refocusing on servers,” 27th Conference on Computer Communications. IEEE INFOCOM 2008, pp.1355–1363, April 2008.

[7] H. Yaiche, R. Mazumdar, and C. Rosenberg, “A game theoretic framework for bandwidth allocation and pricing in broadband networks,” IEEE/ACM Trans. Netw., vol.8, no.5, pp.667–678, Oct. 2000.

[8] S. Cho and A. Goel, “Pricing for fairness: distributed resource allocation for multiple objectives,” Proc. ACM Symp. Theory of Computing, 2006.

[9] Z. Yang and H. Ma, “Hotspot avoidance for P2P streaming distribution application: A game theoretic approach,” IEEE Trans. Parallel Distrib. Syst., vol.20, no.2, pp.219–232, Feb. 2009.

[10] K. Eger and U. Killat, “Bandwidth trading in unstructured P2P content distribution networks,” Proc. Sixth IEEE International Conference on Node-to-Node Computing, pp.39–48, Sept. 2006.

[11] R.T.B. Ma et al., “Dynamic bandwidth auctions in multilayer P2P streaming with network coding,” IEEE/ACM Trans. Netw., vol.14, no.5, pp.978–991, Oct. 2006.

[12] C. Wu, B. Li, and Z. Li, “Incentive and service differentiation in P2P networks: A game theoretic approach,” IEEE Trans. Parallel Distrib. Syst., vol.19, pp.806–820, 2008.

[13] GLICKSBERG, IL, “A further generalization of the Kakutani fixed point theorem, with application to Nash equilibrium points,” JProc. Am. Soc., vol.3, pp.170–174, 1952.

[14] E. Setton, J. Noh, and B. Girod, “Rate-distortion optimized video node-to-node multicast streaming,” Proc. ACM Workshop Advances in Node-to-Node Multimedia Streaming (P2PMMS ’05), pp.39–48, 2005.

[15] J. Sommers, P. Barford, N. Duffield, and A. Ron, “Improving accuracy in end-to-end packet loss measurement,” Proc. SIGCOMM 2005.

Fang Zuo received the B.Sc. degree in computer science in 2005 and the M.S. degree in applied mathematics in 2008, both from the Henan University. He got his Ph.D. degree at East China Normal University, 2013. Now, he is an associate-professor in Henan University, China. His research interests are in P2P networks, distributed multimedia systems, algorithmic game theory and mathematical optimization theory.

Wei Zhang is now a professor of department of Computer Science & Technology in East China Normal University. His research interests are wireless sensor network, computer networks and communication technology, network applications and management, network protocol conformance testing.