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Design Space of Online Bandwidth Trading Markets for P2P Streaming Systems

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***Abstract*—With substantial increase in the connection speed of Internet users and growing demand for high-quality video streaming services, provision of enough resources in P2P streaming systems to guarantee high streaming rate becomes a challenging task. The current works for the deployment of *helper* peers as bandwidth boosters in the P2P streaming systems does not model dynamic resource trading inside the system and lack incentive mechanisms to guarantee helpers' participation. The continuous join/leave of peers in different video channels, time constraints on their duration of stay in the system, and limited information about the internal benefits and costs of peers make the conventional static, offline mechanism design schemes impractical. In this paper, we investigate the challenges of deployment of a online bandwidth trading platform designed for P2P streaming and explore the different design options that are specific to these systems. A new two-sided bandwidth market among peers and helpers is also formulated and an online truthful auction mechanism is proposed which results in higher social welfare compared to the offline algorithms.**

***Keywords*—P2P Systems; Online Mechanism Design; Double Auction; Bandwidth Trading Market; Helper-assisted Streaming**

I. INTRODUCTION

Peer-to-peer (P2P) streaming applications are very popular on the Internet today and Internet-scale P2P streaming systems like PPTV [1], PPStream [2], QQLive [3] and SopCast [4] provide hundreds of TV channels and serve millions of Internet users every day. According to Cisco's Virtual Networking Index report , today, global P2P live video systems have generated over 1,840 petabytes Internet video traffic per month, and is growing at a rate of 33% annually. In P2P multi-channel systems, the resource imbalance among different video channels is a common challenge because of continuous changes in popularity of video channels and dynamic leave/join of viewers during time [5, 6]. As peers arrive and depart the video overlays, some channels face bandwidth deficit, while other overlays have unused upload bandwidth capacity. The peers with unused, surplus upload bandwidth can join to the other channels as *helpers* to alleviate the workload on the streaming server, providing stream for some peers as new stream sources [7].

The power of helper concept relies on the quality and quantity of helpers' participation in contributing their resources to the P2P system. The main hurdle lies in the lack of efficient *incentive mechanisms*. Specifically, the existing works [8] assume the participating helpers as altruistic volunteers and thus, their willingness of participation is not an issue at all. However, the employed helpers to contribute their upload bandwidth to the system will consume their own resources. Therefore, it is natural that the peers with surplus bandwidth will not help the system, unless they are sufficiently incentivized.

Dynamic nature of P2P streaming systems further complicates the incentive mechanism design. A system is dynamic if its participants arrive and depart over time [9], the valuation of each participant is changing [10], or both. In real P2P streaming systems, the helpers join a video channel for a specific period of time and have a specific, private value (bid) for their surplus upload bandwidth. The main challenge in this setting is that decisions on accepting or denying the submitted bid from helpers have to be made *dynamically*, without knowledge of future participants and the supply-demand dynamics. This settings result in an *online bandwidth trading market* in which helpers arrive in a *sequential* order to offer their helping service, and the system should decide whether or not to receive the service as the helper arrives. The other complication arises from the two-sided nature of market in which multiple peers as bandwidth requesters should be matched sequentially to the multiple helpers as bandwidth suppliers.

Nevertheless, the most popular incentive mechanisms [11, 12, 13, 14, 15] are *static* and *offline*, in which the concurrent presence of all the helpers is required. These offline mechanisms assume that all peers will stay from the very beginning of system operation and cannot accept new offerings afterwards. In summary, all the offline schemes fail in a more realistic, dynamic setting of P2P system.

The processes of online decision making occur in many multi-agent systems such as cloud computing [16], mobile crowdsourcing [17], cognitive radio networks [18] and online advertising [19]. The main theoretical research directions in this area include learning on online auction [20], multi-armed bandit and regret minimization [21], online procurement market [22], revenue management [23], and online mechanism design [24]. Traditionally, mechanism design has focused on static settings where the participants are known before the mechanism makes any decision. However, the peers in P2P systems dynamically arrive and depart over the time. Mechanism design for dynamic settings is necessary not only to solve problems in actual dynamic systems, but also because existing solutions for static settings are insufficient in dynamic environments. In online mechanism design, the participants are arriving and departing over time, the private information of each participant is changing over time, or both. Despite the rich literature on online decision making mechanisms, there are many challenges which inhibits deployment of an online bandwidth trading market.

The first difficulty in design of an online market for P2P streaming systems lies in the way it should be integrated in the existing P2P platforms. To our best of knowledge, there is no P2P system which support online resource trading with dynamic resource valuation and incentive provisioning. Although the reputation scores in the P2P reputation systems like BarterCast [25] can be used as incentive for the participating helpers, it is not clear that how helper role can be defined and the online decision making process for each peer can be implemented in these systems.

Another challenge facing deployment of online bandwidth market is the tough time constraints on the demand request of peers in the streaming systems. Unlike the popular tasks in the crowdsourcing platforms (e.g. image labelling), the bandwidth demand in the streaming systems is subject to hard deadlines and can not be delayed or preempted.

To study these challenges in a uniform framework, we explore the design space and implementation issues of online P2P bandwidth trading market, providing insights on the suitability of current solutions and techniques for the problem in hand. Although there are similar efforts in the other contexts (like mobile crowdsourcing [26]), they consider the domain-specific issues in their model and so, their results could not be applied directly to the P2P streaming domain. We then investigate a few specific models that appear promising in that they capture the salient aspects of the problem. Then, we formulate an online bandwidth market for helper-assisted systems and propose a truthful online mechanism with desirable characteristics.

The rest of paper is organized as follows. We first define the problem of online bandwidth trading in P2P streaming systems in Section 2 in a broad sense and explore the design options in it subsections. In Section 3, the possible, existing solutions for the online bandwidth trading are discussed which provide directions for future works. In Section 4, we formulate a two-sided online market for bandwidth exchange in helper-assisted P2P streaming systems and propose a online mechanism that is shown to be truthful and efficient compared to the offline algorithms in Section 5. The paper is concluded with some discussions about the suggestions for the future works.

II. DESIGN SPACE OF ONLINE P2P BANDWIDTH MARKET

To study and understand any particular aspect of repeated decision making for P2P bandwidth trading markets, one must first determine a model or framework in which to work. In this section, we identify a variety of modelling choices for repeated decision making in P2P bandwidth trading market, which includes system design, incentive design, and payoff design categories. For this purpose, we first describe the online decision making in P2P bandwidth market as online mechanism design problem.

A. Problem Description

Consider a P2P streaming system consisting three parties: helpers, peers, and the streaming server(s). The streaming server provides a variety of video channels to which peer can subscribe to watch and share for others. Peers can join to/leave the system arbitrarily and the peers' churn rate is unknown to the system. The peers can receive the video segments for each channel in a client/server or peer-to-peer fashion. In the cases that the bandwidth demand for some (parts of) video streams exceed the total supplied bandwidth through the streaming server and peers, system enters the bandwidth deficiency state. In this state, a bandwidth exchange market is set up by the system, aiming to compensate the bandwidth deficit of system from the unused resources of participating peers in the system. This mechanism can be held among the peers or centrally arbitrated by the server.

The upload capacity of helpers is the item which will be traded in this market. We envision the bandwidth requests of peers as a well-specified *job* considering the time constraints and valuation of peers. Over time, peers join video overlay(s) and submit their available upload bandwidth capacity and possibly, its valuation. Helpers get matched with peers with bandwidth deficit, share the video stream, and receive incentives. Helpers and peers may join to/leave the system over time. Some helpers may provide higher quality streaming service than others. All parties make repeated decisions over time and can learn over time, which may help them in their decision making. All decision makers receive partial feedback: they see the consequences of their decisions, but typically they do not know what would have happened if they had made different decisions. Helpers and peers can behave strategically, so their incentives need to be taken into account. The problem is to design algorithms for decision making, on behalf of the system, the peers, or the helpers.

We can think about this setting from the point of view of each of the three parties, who face their own choices and have different motivations. Peers can choose the maximal price they are willing to offer for a given job, and specify any budget constraints that they have. The system may match (subsets of) peers to (subsets of) helpers. In principle, the system may also be able to modify the offered prices, within constraints specified by the peers, and to determine how to charge peers and/or helpers for their use of the system. In the long run, the system cares about maximizing long-term revenue. In the short term, the system may care about keeping helpers and peers happy to attract more business, especially in the presence of competing systems. Helpers can decide whether to accept a job at a given price, and how much resource to put into it. They may be able to choose among jobs, and may be asked to provide some information such as their asking prices. Helpers care about the amount of money that they earn and the cost of their resource.

Three versions of the problem can be designed: peer-side, helper-side and system-side. The peer-side problem is to design a mechanism which makes repeated decisions for a specific peer. The system-side problem is to design a mechanism which makes repeated decisions for the system. The helper-side is to propose a mechanism which makes online decisions for the helpers. Figure 1 shows the design space of online P2P bandwidth trading market and the potential approaches for formulation.

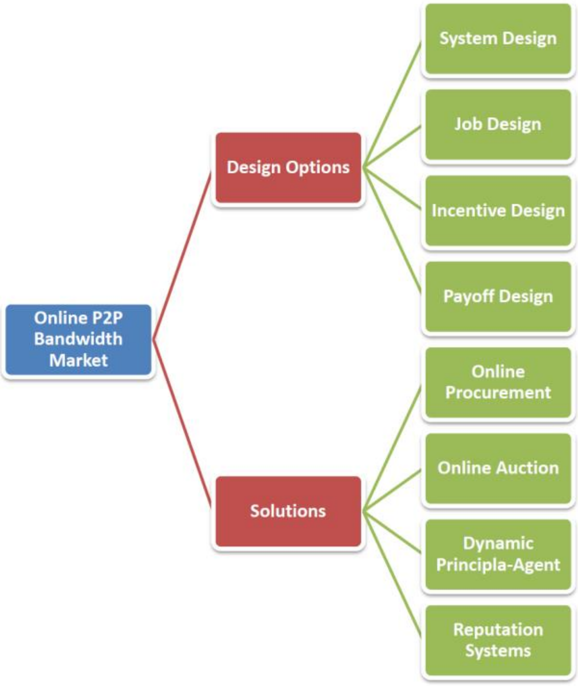

Figure 1: Design space of online P2P bandwidth trading market and its potential solutions

B. *System Design*

All the interactions among helpers and peers take place in the context of a particular P2P system. The system designer controls the way in which peers and helpers may interact.

Peer dynamics: How does the peers are notified about the arrival or departure of other peers (including helpers)? The helpers depart the system when can not accomplish any bandwidth request or do not have enough motivation to participate in the resource exchange market.

Selection of helpers: The peers prefer to receive the streamed video over the higher capacity links with less delay. Does the system allow peers to limit their jobs to the specific helpers with higher quality, and if so, how?

Selection of Peers: In private P2P communities, the peers should always keep their upload-to-download ratio (know as sharing ratio) higher than a threshold to avoid being expelled from the community [27]. In these systems, peers prefer to select peers with more downloading potential for seeding. Does the system allow the helpers to select from among the requesting peers?

Selection of jobs: How does the system allow helpers to select jobs? Does a helper see all offerings that are currently in the market? If so, how are they sorted? Alternatively, the system could limit the options presented to a given helper. When the job(s) from a given peer are offered to a given helper, does the system allow the peer to restrict which offerings from other peers this helper is exposed to?

Price negotiation: How do peers negotiate prices with helpers? Typically it is assumed that peers post one take-it-or-leave-it price, but this is not the only possibility. Can a peer post different prices to different helpers depending on the helpers' characteristics? Can the peer update the price over time? Alternatively, one could imagine a P2P system on which helpers communicate minimal asking prices to the peers and prices are determined via an auction.

Payments: How do payments happen? The simplest version is that each helper, upon completion of a job, receives the posted price for that job. Can a peer specify a payment that depends on the quality of stream experienced by the peer? If so, must he declare the exact payment policy up front? What is the type of transferred currency in the system? With the spread of Bitcoin [28] as the mostly accepted P2P digital cash, it is a natural question that how helpers and peers can estimate their cost and benefits in terms of this currency.

System-wide reputation: Does the system maintain a system-wide reputation score for each helper and/or peer? If so, then how exactly is this score defined? What properties of this score are guaranteed? How are reputations used? How are helpers and peers prevented from manipulating their own reputations and the reputations of others?

Information dissemination: How do the information about the jobs and peers is disseminated in the system? In real P2P systems, peers have partial view about their neighbourhood and resource availability in the system that it can affect the performance of resource trading in the market. Due to the lack of central trusted entity in the pure P2P systems, the participation of peers is subject to their updated information about the online status of the system, i.e., the up-to-date information about the resource supply and the associated costs.

Security concerns: How does the system prevents peers to misreport their available resources and valuations? How does the P2P system is protected against the free-riders? How can peers trust to the transferred currency in the system? How is the mechanism is protected against the pollutions and whitewashing attacks? Although some of these concerns are addressed in [29, 30], there is more space to provide proven solutions for these concerns.

C. Job Design

Job design options heavily depend on the purpose of P2P streaming system (live vs. video-on-demand (VoD)) and its unique characteristics (like social relationships, type of peer connectivity, content coding, etc.). Each task which is advertised in the system have a (possibly hard) expiration deadline, which is a distinctive features of bandwidth requests in P2P systems. The defined jobs in the P2P streaming system may require additional resources beyond the job specification. For example, a bandwidth request job for some video segments in VoD requires cache allocation by the helpers in the requested time window.

Job specification: The jobs can be classified based on the type of video stream (i.e, live or on-demand). In the live streaming setting, the bandwidth requests can be submitted for the different coded video layers. Each job has also an associated deadline which corresponds to the playout delay. In the VoD streaming, the bandwidth requests are submitted for the specified missed video segments based on the segment availability matrices advertised by the helpers. There is an associated expiration deadline for each video segment which is determined based on the playback position of requesting peers. The time interval of segment availability also depends on the cache size constraint in the helpers. So, it seems that a job specification language should be designed to generalize the requests into a consistent form.

Job advertisement: How does the helpers and peers submit their bids and jobs? In a procurement market, how can helpers announce their pair of (resource,value) to the system? In a pure P2P bandwidth market, is it possible to advertise jobs and bids without relying to a central authority?

Quality measurement: The amount of achieved incentives for the resource trading in the online P2P market should be directly proportional to the quality of jobs accomplished by the peers. In this way, the helpers will not have motivation to exaggerate about their capacity for doing more jobs than their true capability. Quality-of-Experience (QoE) and Quality-of-Service (QoS) are the most accepted measures to assess the quality of streamed videos to the viewers. A possible approach for the quality measurement problem is to deploy an accounting module in the system which is responsible to monitor activities and record the outcome of accomplished job. Although this solution is partially possible in the hybrid CDN-P2P streaming systems, the problem still remains in the pure P2P systems in which peers only rely on the volunteer reports by the other peers in the system. The work [31] proposes a distributed accounting mechanism based on the reputation scores for the distributed work systems in which there is no trusted currency. This mechanism is incentive-compatible and addresses the security concerns about Sybil attacks. However, there is no real implementation of this mechanism in the P2P systems and more elaborations are required on the information dissemination protocol to incorporate the wide range of job specification and advertisement options.

D. Incentive Design

One of the most difficult aspect of formalizing the repeated decision making problem in a dynamic P2P streaming system is modelling the incentives of participants. In the economics literature, it is standard to model agents as self-interested and rational utility maximizers. A large body of literature on the incentive mechanism design for P2P systems is focused on the free-riding, while we need an incentive mechanism that rewards the high quality services more.

Rationality: Do helpers behave rationally when choosing jobs to complete at particular prices? The standard model from economics is that each helper maximizes a simple well-defined notion of “utility,” (an increasing function of) payment received minus associated cost.

Amount of contribution: Can the helpers strategically alter the amount of resource that they provide for a given job, or is it assumed that helpers complete each job as expected?

Costs: How do the helpers evaluate their costs for completing a given job?

Myopia vs. long term strategies: How myopic are the helpers? When making a decision about a particular job, do they take into account the effects of this decision on their future?

E. Payoff Design

The statement of an algorithmic problem should include a specific performance objective to be optimized, perhaps under some constraints.

Peer payoff: A peer-side decision making algorithm typically maximizes the utility of this peer, i.e., the value of supplied bandwidth minus the payment to the helpers. If the peer has a pre-specified budget, the algorithm may instead maximize the value of completed jobs subject to budget constraints. In incentive-compatible mechanisms that elicit helpers’ private costs, one may wish to optimize the social welfare – the utility of the peer plus the total utility of the helpers – or some other weighted sum of these two quantities.

System-side objective function: For system-side algorithms, the performance objective might take into account the utility of peers, helpers, and the system itself. Assuming the system receives a fixed percentage of every transaction, the system’s revenue is simply a fixed fraction of the total payment from peers to helpers. One reasonable objective is a weighted sum of the system’s revenue and the total utility of the peers; the choice of weights is up to the system. Moreover, the system may wish to ensure some form of fairness, so that no peers are starved out. Further, the system may have additional forward-looking objectives that are not immediately comparable with the system revenue and peers’ utility, such as the market share and the helpers’ satisfaction (to encourage helpers to help the system in the future).

Helper payoff: The helper-side algorithm should maximize the utility of helper, i.e., the payments received from the peers minus the cost of upload bandwidth sharing.

III. POSSIBLE APPROACHES FOR ONLINE BANDWIDTH TRADING: A REVIEW

A. Online Procurement

In an online procurement market, helpers as *sellers* arrive in a sequential order to offer their service, and the streaming server as *buyer* decides whether or not to buy up the peer's sharing service as it arrives. Naturally, each helper wishes to be compensated for her service, while the buyer in turn has limited budget and aims to procure the upload bandwidth sharing from the helpers that maximize her utility. Each iteration in a dynamic procurement market follows a simple rule: each helper posts a price which can be either accepted or rejected by the buyer. There are two limitations in the dynamic procurement markets which complicates the process of decision making: 1) the helpers' true cost for upload bandwidth sharing are unknown to the system and may be misreported, and 2) the sequential arrival and departure of peers which requires making decisions with partial information of the market.

To address the first constraint, mechanism design theory advocates for truthful mechanisms, which incentivize every participating helper to reveal her true cost for stream sharing. In procurement markets, the challenge is then to design truthful mechanisms that yield a favourable outcome for the buyer under its limited budget. That is, optimize the buyer's utility under some fixed budget.

The second limitation is because of the online arrival of the peers. Following the literature on online algorithms, there are three distinctive ways in which the arrival sequence of the agents is modelled.

adversarial model where an adversary chooses the arrival sequence of the helpers and their bids in a manner that yields the worst possible outcome for the mechanism.

secretary model which assumes the values for the bids are chosen adversarially, though the arrival order is chosen uniformly at random from the set of all possible permutations of the peers.

independent random model where each peer is independently drawn from some unknown common distribution.

A procurement market can therefore be characterized in terms of the payoff function the buyer wishes to optimize, and the arrival model of the peers. The goal is to design truthful budget feasible mechanisms that maximize the buyer's utility. Peers can express their cost in two ways: *bidding model* in which a bidding mechanism learns the costs by soliciting a bid from each peer upon its arrival and *posted price model* in which each helper is faced with a (possibly different) offer that can be either accepted or rejected. The bidding model is often considered unnecessarily complex, especially from the standpoint of the bidders, while the Posted price mechanisms are compelling due to their simplicity and are the most commonly used form of pricing.

Online procurement and dynamic pricing has been recently received more attention in the Electronic Commerce [22], crowdsourcing [32], and dynamic supply chain management [33]. The main challenge for applying these models in the P2P context is the way that these mechanisms should be implemented and deployed in the current P2P systems.

B. Online Double Auction

The microeconomic-based auction mechanisms has been attracted more attentions in the recent years [34, 35]. In the these existing works, it is assumed that either supply or demand side in the market is dynamic, but not both. In online double auction markets, e.g. online P2P bandwidth markets, the dynamics are two-sided, i.e. both the supply and the demand are dynamic.

An online double auction mechanism has to match sellers and buyers dynamically and calculate a payment for each matched trader without knowing about future orders. Such uncertainty is more challenging for double auction mechanism design because modelling traders' bidding behaviour in double auctions is very complicated even in a static case [36]. Some recent studies have been conducted to study online double auctions form the theoretical and application apsects [21, 37]. One of the critical features of every online auction mechanism is truthfulness, which guarantees that traders' manipulations in their capacity or cost is not profitable. Thus a robust mechanism that can prevent traders' manipulations or quickly adapt to market changes is very desirable in an online double auction market. Perhaps surprisingly, we have not observed any works towards the design of online auction mechanisms for P2P systems. There is further room for research and development of real online bandwidth trading markets that seems has strong potential for improving the quality of streaming services in the P2P systems.

C. Dynamic Principal-agent Mechanisms

The standard principal-agent problem [38] is set in a static setting, in which the principal offer a posted price (i.e., take-it-or-leave-it) contract to the agent.The contract is designed so as to motivate the agent to perform the offered job according to the preferences of the principal. In return for his performance, the agent receives a contractual reward from the principal which is conditional on the outcome of his activities. In dynamic principal-agent scenario, the helpers as agents can strategically change their sharing service levels depending on the price or contract that they are offered. The chosen sharing service level probabilistically affects the quality of received video stream by the peers, determining a distribution over the possible quality of service classes. Each helper is characterized by a mapping from service levels to costs and distributions over the quality of service classes; this mapping, called helper's type, is known to the helper but not to the mechanism. The choice of service level is not directly observable by the peer, and cannot (in general) be predicted or inferred from the achieved streaming rate.

Posted pricing is not adequate to incentivize helpers to offer high quality streaming service in this setting since helpers could allocate the minimal amount of their upload bandwidth without any loss of reward. Instead, the system as principal may want to use more complicated contracts in which the reward may depend on the quality of the achieved streaming service. Note that contracts cannot directly depend on the helper's service level, as this parameter is unknown to the system. A possible solution is that the mechanism adjusts the offered contract over time, as it learns more about the helper's behaviour.

To simplify the problem, one can assume that helpers are myopic, and that the quality of streaming service is immediately observable. Even with these simplification and ignoring the issues of task assignments, the repeated principal-agent setting described above is significantly more challenging than dynamic procurement. The space of possible contracts and possible job types are extremely larger than their counterparts in the dynamic procurement, and the mapping from an action to system's expected utility is more difficult to characterize and analyze.

A little work has been done in the dynamic principal-agent settings [39]. For the online setting, [40] proposes a bandit learning mechanism for the repeated principal-agent problem in which principal learns over time to set the rewards. This basic algorithms assume that a single item is sold in each round and there is no limit on the principal budget. It seems that this area requires more efforts for improvement of current algorithms, together with deployment of these mechanisms in the realistic P2P systems.

D. Reputation Systems

Reputation mechanisms are deployed in the P2P systems to encourage resource sharing among peers and combat malicious user behaviours. Reputation management help peers to assess the trustworthiness of others and select more reputable peers for interaction. Persistent reputation scores for helpers may help limit spam and encourage higher quality of streaming for the end users. Likewise, persistent reputation scores for peers may encourage peers to be more considerate towards the helpers. Thus, one may want to design a stand-alone "reputation system" which defines and maintains such scores, as a tool which can be used in conjunction with different higher-level algorithms to incentivize high quality services. Reputation systems may be designed to address issues related to either moral hazard (when helpers' contribution is desirable but not immediately observable) or adverse selection (when similar helpers may be different from one another, and it is desirable to entice helpers who has better link quality and provide higher streaming rates), or a combination of the two.

The design of reputation systems has been extensively studied in different contexts (e.g. electronic-commerce, adhoc networks, etc.) [24, 41]. Also, there is rich literature on the issues of reputation management in P2P environments [42, 43, 44, 45, 46, 47]. Some works has specifically addressed the attacks and their countermeasures in the area of P2P streaming [30]. However, there are many restrictions for deployment of online resource trading markets on top of these systems. The first challenge is that the online job allocation and reputation management algorithms are highly interrelated. For example, the job assignment to a specific helper is essentially based on the accumulated reputation score of helper. On the other hand, the reputation algorithm should take into account the logic of job assignment algorithm to compute the reputation of helpers. It seems that separate design of these algorithms will result in sub-optimal performance.

Another challenge comes from the highly dynamic and distributed nature of P2P systems. Recently, some researchers have successfully deployed distributed reputation management mechanisms in the P2P systems without relying on a central authority; see, for example, BarterCast [25] and DropEdge [31]. It is proven that these systems are resistant to the common security attacks and scale well in real Internet deployment. However, there are many questions that should be answered in this area. For instance, it not clear that what is the relationship between the quality of received service in peers and amount of received reputation score in the helpers. Also, more elaborations are required to integrate the commonly accepted Bitcoin [28] as digital currency into these platforms. Is there any quantitative relationship among the reputation score of a peer with its received Bitcoin from other parties?

E. Online Two-sided Bandwidth Auction

In this section, we try to design an online P2P bandwidth market based on the design options which are described in Section 2.

1) Design Specification

System design. We envision the problem of matching a subset of autonomous helpers in a dynamic P2P live streaming system with a subset of viewing peers. Each party arrives in some period and is present in the system for some finite period of time. An agent is either a seller, able to provide the streaming service as requested, or a buyer, with a bandwidth demand to satisfy. Moreover, both peers and helpers are assumed to be self-interested and willing to misreport their private information (like arrival and departure times and resource valuation) if this can improve their received incentive. Is is assumed that all peers can receive video stream from the all helpers present in the system. The helpers can see all the submitted bandwidth demand requests and there is no restriction on the helper's view on the posted requests.

We consider a trusted, unforgeable currency in the system like Bitcoin [28] which is transferred in the bandwidth transactions between peers and helpers. These payments act as incentive to combat free-riding in the P2P system. For simplicity, we assume now that all the parties in the market have access to the current information about the present helpers and peers and their offerings. The complex online decision making processes of the helpers and peers are modelled with analytical tool of online two-sided auction [48, 49, 50]. We consider an online two-sided market with discrete time periods $T = \{0,1,2,\cdots\}$ in which buyers and sellers that arrive and depart over time are interested in trading a single unit of upload bandwidth. In case of multi-unit items, it is assumed that each buyer submits multiple requests to the system [51-54].

Job design. For simplicity, a single overlay setting is assumed in which all the bandwidth demands are submitted All jobs are identical, and any present helper can perform a job. All jobs are completed in a unit period of time. The arrival, departure, and cost (if a seller) or value (if a buyer) are all private information to the participants. Each participant peer (buyer or seller) $i \in P$ is characterized by a private *type* $v_i = (a_i, d_i, r_i, w_i) \in V$, where $r_i = \{b, s\}$ determines whether a peer is buyer (*b*) or seller (*s*), $a_i \in T$ is the arrival time, and $d_i \in T$, with $d_i \geq a_i$, denotes the departure time. For a buyer, $w_i \in \mathbb{R}_{\geq 0}$ denotes its value for buying one unit of bandwidth. For a seller, $w_i \in \mathbb{R}_{\leq 0}$ defines its value for selling one unit of bandwidth while present. For a seller, departure period is the final period in which it is interested in receiving payment and for a buyer, departure time is the final period in which it values the bandwidth units.

Incentive design. Peers are assumed to be selfish, and the type is private information. A peer's selfishness is shown in its willingness to misreport its type when this will improve the outcome of auction in its favour. It is also assumed that peers can not understate their arrival time or overstate their departure period, all peers have a bounded patience, and no false-name bids and no collusion is possible. Other misreports are allowed. It is also assumed that helpers are myopic agents, try to maximize their instantaneous utility.

Payoff design. We assume a quasi-linear payoff function for peers, so that the net utility for a trade x in some price p is the received value from the trade minus the payment.

F. Definitions

Now we define the basic concepts in the online two-sided auction.

[Two-sided Auction (TA)] A two-sided auction (TA) is defined as a tuple $M = (g, \tilde{p})$, with *allocation policy*, *g*, and *payment policy*, $\tilde{p}$.

The allocation policy $g_i(\tilde{v}_{\leq t}, t) = 1$ determines that peer i buys a bandwidth unit in period t, given bids $\tilde{v}_{\leq t} = \{\tilde{v}_j = (\tilde{a}_j, \tilde{d}_j, \tilde{w}_j) : \tilde{a}_j \leq t\}$, and $g_i(\tilde{v}_{\leq t}, t) = -1$ determines that peer i sells a bandwidth unit in period t. Allocation $g_i(v) = \sum_{t' \in [a_i, d_i]} g_i(v_{\leq t'}, t')$ indicates whether peer i gets the bandwidth unit in any period, and $g_i(\hat{v}_i, v_{-i})$ means the allocation of peer i given that the bids from the other peers are v_{-i} and peer i bids $\hat{v}_i$.

The payment policy $p_i(\tilde{v}_{\leq t}, t) \in \mathbb{R}$ indicates a payment made by a peer i to the auctioneer in period t. If $p_i(\tilde{v}_{\leq t}, t) \leq 0$, this will be a payment from the auctioneer to the peer. In TA, we want to have $g_i(\tilde{v}_{\leq t}, t) \geq 0$ for all buyers, with $g_i(\tilde{v}_{\leq t}, t) = 1$ in at most one period $t \in [a_i, d_i]$ and zero otherwise. Payments can only be made when a peer is present. Payment $\hat{p}_i(v) = \sum_{t \in [a_i, d_i]} g_i(v_{\leq t}, t)$ is the total payment over all the periods in its presence interval, and $\hat{p}_i(\hat{v}_i, v_{-i})$ means the payment by peer i given that bids from the other peers are v_{-i} and peer i bids $\hat{v}_i$. We define $L(v_i) \subseteq V$ as the set of all reports for type v_i, which contains all the types $\hat{v}_i \in V$ for which $\hat{a}_i \geq a_i$.

[Truthfulness] A mechanism $M = (g, \hat{p})$, where g is an allocation policy and $\hat{p}$ is a payment policy, is truthful if for any peer i and any v_i, we have $v_i(g_i(v)) - \hat{p}_i(v) \geq v_i(g_i(\hat{v}_i, v_{-i})) - \hat{p}_i(\hat{v}_i, v_{-i})$, $\forall \hat{v}_i \in L(v_i)$ and $\forall v_{-i}$.

[Profitability] A mechanism $M = (g, \hat{p})$ is profitable if:

$$\textstyle\sum_{i:d_i<t} \hat{p}_i(v) + \sum_{i:a_i \leq t \leq d_i} \sum_{t' \in [a_i, t]} \hat{p}_i(v, t') \geq 0, \forall t, \forall v. \quad (1)$$

Profitability condition requires that the auctioneer has money in hand in each period.

[Feasibility] A mechanism $M = (g, \hat{p})$ is feasible if:

$$\textstyle\sum_{i:d_i<t} g_i(v) + \sum_{i:a_i \leq t \leq d_i} \sum_{t' \in [a_i, t]} g_i(v, t') \geq 0, \forall t, \forall v. \quad (2)$$

G. Online Bandwidth Trading Algorithm

With this definitions in hand, we develop an online two-sided auction scheme (OTA) for the proposed system that follows [7]. Each OTA is characterized by a price schedule, f_i, coupled with a matching policy, which together define the allocation and payment policies.

1) Allocation Policy

To describe the matching policy of online mechanism, the threshold price first should be defined.

The threshold price, $\tilde{ps}_i$ to peer i in period t is defined as:

$$\tilde{ps}_i = \max_{\tau \in \{d_i - k, \cdots, t\}} f_i(\tau, r_i, v_{-i}), \forall t \in T \quad (3)$$

until the bid is matched or departs.

The matching policy of OTA determines the allocation policy.

2) Allocation policy of OTA

In each time slot $t = 1, 2, \ldots$ for each active bid in the period t, compute the new price $f_i(t, r_i, v_{-i})$ to each active bid. Mark all active bids for which $f_i(t, r_i, v_{-i}) \geq w_i$ as priced-out. Update $\hat{ps}_i(t) = \max\{\hat{ps}_i(t-1), f_i(t, r_i, v_{-i})\}$ for the remaining active bids. Sort the active bids into a bid book, in order of decreasing price $f_i(t, r_i, v_{-i})$. Sort the active asks into an ask book, in order of decreasing price $f_j(t, r_j, v_{-j})$ and break ties at random. Match bids and asks while $f_i(t, r_i, v_{-i}) + f_j(t, r_j, v_{-j}) \geq 0$. Set the payments to a matched bidder as $\hat{p}_i(v) = \hat{ps}_i(t)$.

3) Payment Policy

At the start of period t, bids in the auction that are in the acceptable period (i.e. $t \in [a_i, d_i]$) will be in one of three states: matched, priced-out, or active. A matched bid will definitely trade and its price has been determined. A bid is priced-out when the auction has determined that it will definitely not trade. An active bid is neither priced-out nor matched, and whether or not it will trade remains uncertain. For all bids and all periods t while a bid is active or not yet arrived, a *valid price schedule* $f_i(t, r_i, v_{-i}) \in \mathbb{R}$ is defined to determine the price to buy or sell a bandwidth unit in period t given bids v_{-i} from other agents.

[Validity] A price schedule, f, is valid if it meets each of the following conditions in any period t before a bid is priced-out or matched:

1. Price $f_i(t, r_i, v_{-i})$ does not depend on the arrival time, departure time, or on the reported value of bidder i.

2. Price $f_i(t, r_i, v_{-i})$ does not depend on the bids that arrive after period t.

3. While $f_i(t, r_i, v_{-i}) \le w_i$ the price does not depend on the value of any bids $j \ne i$ that are active at the start of period t and have $f_j(t, r_j, v_{-i}) \le w_j$. Otherwise, if $f_i(t, r_i, v_{-i}) > w_i$ then we also have $f_i(t, r_i, v_{-i}) > w_i$ for all values of bids $j \ne i$ that are active at the start of period t while $f_j(t, r_j, v_{-i}) \le w_j$.

The first condition satisfies the peer's status independence and the second one ensures online computability. The third property informally states that if you might still trade, then your bid should not affect the price of other bids that might still trade or whether or not other bis are priced-out.

The main constraint for a price schedule to be valid is that the price in each time period should be independent of the active bids in that period. One of the possible solution is *exponentially-weighted moving average* on a statistic of all offers in the current period. An exponentially-weighted moving average price is defined for the buyers as

$$f_i(t, b, v_{-i}) = \lambda z(v_{t-1}) + (1 - \lambda) f_i(t - 1, b, v_{-i}) \quad (4)$$

and for the sellers as

$$f_i(t, s, v_{-i}) = -\lambda z(v_{t-1}) + (1 - \lambda) f_i(t - 1, s, v_{-i}) \quad (5)$$

where $\lambda \in [0,1]$ is the smoothing factor, and $z(v_t)$ is some statistic of values of all offers including matched, priced-out and expired ones. It is shown in the simulations that *mean* or *median* of absolute values of bids works well for this settings. The Theorem 1 and 3 proves that the proposed OTA is truthful and profitable. The proposed online auction mechanism $M(g, \tilde{p})$ is profitable and truthful.

Proof. Refer to Theorems 1 and 3 in [55].

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