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Towards strategic bandwidth sharing in overlay multicast networks based on mechanism design theory

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Abstract

The selfish behavior of the users in the overlay multicast networks can lead to degradation of the performance. In this paper, we target the mechanism design for the overlay networks based on the monopoly auction economies. In our proposed auction mechanism, the bandwidth of the service offered by the origin servers can be thought of as commodity. In this auction, the sellers are either the origin servers or the peers who forward the content to their downstream peers. Also, the corresponding downstream peers of each seller play the role of buyers who are referred to as bidders. Each bidder submits a sealed bid to its corresponding seller. The high bidder wins and pays its bid for the service. By theoretical and experimental analysis, we prove that the proposed auction mechanism achieves performance improvements in the overlay network.

Keywords: Multicasting; Overlay Networks; Strategic Behavior Modeling; Mechanism Design; Monopoly Auction

1. Introduction

In most real-world implementations of overlay networks, the administrative domains of the different users are not identical. That is why the users behave selfishly against each other. Consequently, the peers do not tend to forward the multimedia digital content to their downstream peers; resulting in degradation of the performance of the network specially in term of the aggregate throughput.

Literature survey reveals that the designing self-organizing mechanisms is still a hot topic in the area of the overlay multicast networks. There exist two main approaches in order to model the selfishness of the overlay peers- *strategic behavior modeling approach* [1, 2, 3], *non-strategic behavior modeling approach* [4, 5, 6, 7, 8]. In the former, every peer is treated as a game player who seeks to maximize its utility regard to the actions of the other peers, whereas in the latter, the action of the peer is not affected by the actions of the other peers at all.

The research works of [6, 7, 8] are some examples of the market-based approaches which have been maintained so far in the literature. In these designs, it has been assumed that the sellers have perfect information of market demand. Nevertheless, in most state-of-the-art overlay multicast networks which have been designed based on markets, the sellers do not have perfect knowledge of the market demand. Instead, they have only statistical information of the market demand. Only the buyers of the multimedia service, themselves, know precisely how much of the content they are willing to buy. In this paper, we aim to examine this more realistic case for the overlay

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multicast networks. Maybe the simplest situation in which the above assumptions are present occurs when the multimedia content is provided for monopoly auctions. In such a setting, there are a number of standard auction forms- first-price, second-price, Dutch, English [9].

We have presented a framework which employs the theory of *mechanism design* of microeconomics. The mechanism design is relevant to the overlay networks in the sense that how and when the design of an auction can achieve maximization of revenue of the peers. In order to achieve this goal, some private information of the peers is required. By considering the bandwidth of the service offered by the origin servers as the commodity, we design an incentive compatible auction which falls into the category of the strategic behaviour modelling. In this framework, the downstream peers submit their bids for each commodity at the upstream peers. The sellers are either the origin servers or the peers who forward the multimedia services to their downstream peers. For each seller, its corresponding downstream peers play the role of buyers who are referred to as bidders. Each bidder submits a sealed bid to its corresponding seller. The high bidder wins and pays its bid for the bandwidth of the service.

The remainder of this paper is organized as follows: We discuss the related works in Section 2. Section 3 is devoted to proposition of the overlay multicast auction. Section 4 discusses network operations based on the proposed mechanism. In Section 5, we bring about performance evaluation. Finally, we conclude in Section 6.

2. Related Work

To address the selfish behavior of the peers based on the non-strategic behavior modeling method, much of the literature has applied pricing approaches [4, 5, 6, 7, 8]. Cui *et al.* in [4] have proposed a distributed algorithm which maximizes the aggregate utility of the peers subject to both network and data constraints. Wang *et al.* in [5] have presented an intelligent non-strategic model based on optimal control theory.

The most relevant to our work is the one due to Analoui and Rezvani [6, 7, 8] in which they have used microeconomics theories. They are the first to apply the concept of *Walrasian general equilibrium* in order to model the non-strategic behavior of the peers. They have investigated both cases of single-service overlay multicasting and multi-service overlay multicasting.

A few other works have also been proposed to allocate the bandwidth based on strategic auctions [1, 2, 3]. The authors of [3] have presented an auction-based model to improve the performance of BitTorrent. In Wu *et al.* [1], an algorithm is presented which considers conflict-resolving strategies among coexisting overlays for streaming. Also, they have shown in [2] that combining such strategies with network coding-based media distribution leads to efficient multi-overlay streaming.

3. Proposition of Overlay Multicast Auction

This section presents *First-price Overlay Multicast Auction Mechanism (FPOMAM)* which is developed for the single-service case. We consider an application layer multicast network consisting of an origin server and V peers denoted as $\mathsf{V} = \{1, 2, ..., V\}$. The multicast tree consists of the origin server as the root, a set of peers, and a set of physical links. The physical links are in fact the physical connections either the router-router connections, or the router-peer connections. Let us suppose that the network consists of L physical links, denoted as $\mathsf{L} = \{1, 2, ..., L\}$. The capacity of each link $l \in \mathsf{L}$ is denoted by c_l. We represent the directed graph of the multicast session by a $(V+1)\times(V+1)$ adjacency matrix, denoted as $\mathbf{A}$. The $\mathbf{A}_{i,j}$ element of the matrix $\mathbf{A}$ denotes the flow that is originated from node i and is terminated in node j, namely $f_{i,j}$. Also, $x_{i,j}$ denotes the rate of the flow $f_{i,j}$. We put $\mathbf{A}_{i,j} = 1$ whenever there is a flow and zero otherwise. The multicast session consists of some unicast end-to-end flows, denoted as set F :

$$\mathsf{F} = \{f_{i,j} \mid \exists\, i, j \in \mathsf{V} \quad : \ \mathbf{A}_{i,j} = 1\} \tag{1}$$

Each flow $f_{i,j}$ of the multicast tree passes through a subset of the physical links, denoted as

$$\mathsf{L}(f_{i,j}) \subseteq \mathsf{L} \tag{2}$$

Also, the set of the flows that pass through link l is denoted as follows

$$\mathcal{F}(l) = \{f_{i,j} \in \mathcal{F} \mid l \in \mathcal{L}(f_{i,j})\} \quad (3)$$

The set of all downstream nodes of each node i (children of node i) is denoted by $Chd(i)$ as follows

$$Chd(i) = \{v \in \mathcal{V} \mid \mathbf{A}_{i,v} = 1\} \quad (4)$$

Let K_s denote the number of downstream peers of the seller s in the multicast tree who wish to buy the service from the seller s. In fact, K_s accounts for the number of potential children of the seller s. The seller s wishes to sell the bandwidth of the service to one of K_s buyers for the highest possible price. Each bidder submits a sealed bid to the seller s. The high bidder wins and pays its bid for the service.

Buyer i's value for the service, v_i, is drawn from the interval [0, 1] according to the cumulative distribution function (CDF) $F_i(v_i)$, $i \in Chd(s)$ with probability density function (PDF) $f_i(v_i)$, $i \in Chd(s)$. Recall that $F_i(v_i)$ denotes the probability that i's value is less than or equal to v_i, and that $f_i(v_i) = F_i'(v_i)$. Also, we assume that each buyer knows its own value but does not the value of the other buyers. Since the PDFs $f_1, ..., f_{Ks}$, are public information, both the seller and the buyers know these PDFs. Although the seller s does not know the exact values of the buyers, it knows the PDF (equivalently CDF) from which each value is drawn. If the value of buyer i is v_i and it wins the auction, it will pay p. Thus, the utility of buyer i is $v_i - p$. But, if the buyer i does not win the auction, it will pay p and its utility will be $-p$.

For the sake of simplicity, we assume that $f_i(v) = f(v)$ for all $v \in [0,1]$. In order for a bidder to submit its optimal bid, it must know the bid of other bidders. On the other hand, the bids that the others submit are hidden because of the sealed-bid rule. Thus, the bidders are in a strategic setting. Suppose that bidder i's value is v_i. Given this value, the bidder i must submit a sealed-bid, $b_i(v_i)$. The strategy of bidder i is represented as a bidding function $b_i : [0,1] \to \Re_+$. The problem is to find a bidding function $\hat{b} : [0,1] \to \Re_+$ such that it is optimal for each bidder to employ, given that all other bidders employ this bidding function as well.

Roughly speaking, we wish to find a symmetric Nash equilibrium (NE), $\hat{b}(.)$ in bidding functions. Bidder i's expected payoff from reporting an arbitrary value, r, to the seller s when its value is v can be calculated as follows

$$u(r,v) = F^{K_s - 1}(r)(v - \hat{b}(r)) \quad (5)$$

The term F^{K_s-1} in (5) implies that the bidder i will win only when the bid submitted for it, r, is strictly greater than the bid submitted by all $K_s - 1$ other bidders. Also, the term $(v - \hat{b}(r))$ implies that the bidder i pays only when it wins and it then pays its bid, $\hat{b}(r)$. In order for $\hat{b}(v)$ to be NE, it must be the case that $r = v$, i.e., NE occurs when the bidder i reports its true value, v, to the seller s. We state the following theorem without proof. Interested readers can refer to [9] to see the details and the proof.

Theorem 1 (NE of FPOMAM). *For each monopolist seller s, running FPOMAM on its K_s downstream peers, the NE of bidding strategy is that each downstream peer bids the expectation of the second-highest downstream peer's value conditional on winning.*

4. Interactions of Network Based on the Proposed Auction

In this section we provide a brief description of the procedure of joining the new peers to the network based on FPOMAM. Due to space limitation, we do not discuss the procedure of peers' leaving here. The topology map of the network is kept in the database of the origin server and may be modified upon occurrence of every join/leave request. Each new peer v, on joining the network, acquires the list of candidate parents who can serve it via communicating with the origin server. To this end, the origin server seeks the locations of the multicast tree wherein the corresponding seller has an empirical utility greater than or equal to a predefined threshold. We defer the investigation of the empirical utility to (6). The new peer, then, sends separate requests to each of the candidate parents. Each candidate parent corresponds to an auction in which the parent itself is acting as seller whereas the requesting downstream peers are acting as bidders. We already have discussed the details of the FPOMAM in Section 3. Once the seller s decides to sell the service to the appropriate highest buyer, it informs all other auction managers. Each auction manager, then, deletes the information of the winner from its queue because the winner is permitted to buy the service from only one location in the multicast tree.

At the end of this round, the origin server calculates the empirical utility of peer v using the following relation:

$$u_v^{emp} = -\ln(1 + d_{sv} / D_v) - \ln(1 + l_{sv} / L_v) - \ln \sum_{l \in \mathcal{L}(f_{sv})} RLS(l) \qquad (6)$$

The empirical utility in (6) serves to distinguish among different locations of the multicast tree; whichever have better empirical conditions will be offered by the rendezvous point to the new joining peers as their candidate parents. In the last term of (6), $RLS(l)$ denotes the rate of link stress which is defined as follows

$$RLS(l) = \sum_{\forall f_{ij} \in \mathcal{F}(l)} x_{ij} - c_l \qquad (7)$$

5. Performance Evaluation

Path stretch is one of the main metrics in order to evaluate the performance of the overlay networks [10]. The term *stretch* is defined as the ratio of the overlay path length to the direct unicast path length between two peers. Regard to this definition, we simplify the investigation of path stretch, by reducing it to an equivalent metric, known as the overlay *hop count*. Due to space limitations, we state the following theorems without proof.

Theorem 2 (The Worst Number of Overlay Hops (WOH)). *In the multicast tree with F flows and $K_{\max}$ maximum out-degree, when F is large enough, the WOH is expressed as follows*

$$WOH = \log_{\breve{K}}^{[1 + (\breve{K} - 1).(F + 1)]} - 1 \qquad (8)$$

Theorem 3 (The Average Number of Overlay Hops (AOH)). *In the multicast tree with F flows and $K_{\max}$ maximum out-degree, when F is large enough, the AOH is expressed as follows*

$$AOH = \log_{\breve{K}}^{[1 + F.\breve{K} - F]} + (\log_{\breve{K}}^{[1 + F.\breve{K} - F]} - F.\breve{K}) / F(\breve{K} - 1) \qquad (9)$$

Figure 1 shows the effect of the simulated FPOMAM on the WOH and the AOH metrics in comparison with the aforementioned analytical bounds for $K_{\max} = 4$. As is evident from the figure, the WOH of the simulative case is considerably smaller than that of the analytical case. Note that based on (6) and (7), the FPOMAM takes into account the empirical conditions of the existing sellers in order to allocate the bandwidth to the new users. Thus, the protocol avoids the locations of the multicast tree wherein the stress, delay, and loss rate are high.

Clearly, the upper levels of the tree typically experience more link stress than the lower levels. This acts as a barrier against increasing the empirical utility of the sellers located in the upper levels and leaves the burden of bandwidth allocation to the lower levels; resulting in increasing the height of the tree.

On the other hand, the upper levels typically experience smaller delay and loss rate which in turn gives rise to increase in their empirical utility. Thus, there is a tradeoff between these two conflicting factors. That is why the gap between the simulative AOH and that of the analytical case is negligible in Fig. 1.

6. Conclusion

In this paper, we target the strategic first-price auction model for the single-service overlay multicast networks by leveraging the theory of mechanism design of microeconomics. Our results have proved the efficiency of the proposed mechanism. Also, we have shown that the proposed mechanism achieves Nash equilibrium for bidding values of the buyers.

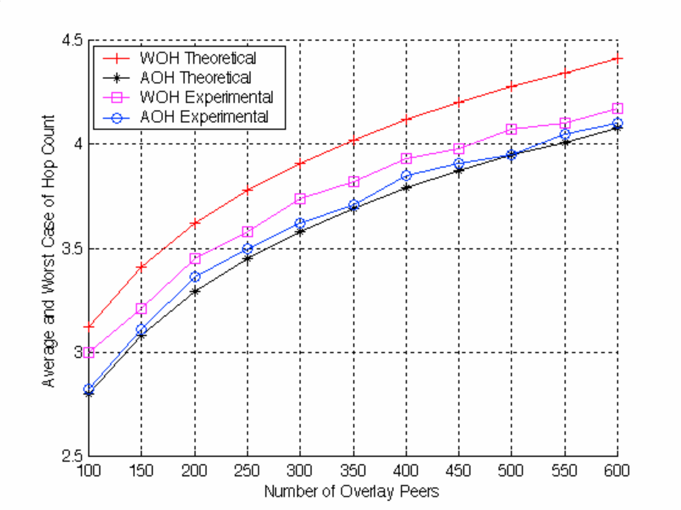

Fig. 1. Average and worst case hop counts for out-degree $K_{max} = 4$

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