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Strategic behavior modeling of multi-service overlay multicast networks based on auction mechanism design

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ABSTRACT

Since the users of overlay multicast networks belong to different administrative domains, they are selfish in nature; resulting in degradation of performance. That is why strategic behavior modeling is a hot topic in the area of the overlay multicast networks. Mechanism design is the most versatile tool for strategic behavior modeling in microeconomics. In this paper, we model the strategic behavior of the selfish peers by leveraging the rich theory of mechanism design using the concept of economic auctions. By considering the bandwidth of services as the commodity, we design a revenue-maximizing auction mechanism. The sellers are either the origin servers or the peers who forward the digital multimedia content to their downstream peers. For each seller, the corresponding downstream peers play the role of buyers who are referred to as bidders. Each bidder submits a sealed bid to the corresponding seller. The highest bidder wins and pays its bid for the service. Also, we derive analytical closed-form expressions for upper bounds relevant to the performance metrics. The experimental validation proves the scalability and the efficiency of the proposed mechanism.

1. Introduction

Overlay multicasting solution has recently been accepted as a paradigm shift in order to distribute the digital real-time contents such as teleconferencing, IPTV, and online video broadcasting in large peer-to-peer (P2P) networks. The overlay multicasting, not only can achieve many of the same design objectives of IP multicasting, but also is easier to implement than it for real-world P2P applications.

In general, the overlay networks can facilitate delivering multiple independent real-time services to the intended recipients. For each service, the flow of data is originated from the corresponding origin server, passes through the underlying physical links, and finally is delivered to the intended users who are known as peers. Each peer, upon receiving the services, can forward them to the downside peers. Since the peers usually belong to different administrative domains, they do not tend to cooperate with each other. It means that each peer is likely to download the content of the service from its upstream peers rather than to upload the data to its downstream peers; resulting in degradation of the level of cooperation in the network and hence decreasing the aggregate throughput.

With respect to this fact that the selfish behavior of the overlay peers is unavoidable in real P2P networks, it turns out that the most important question towards designing the overlay multicast protocols is the following: "How should the selfishness of the peers be exploited, so that the aggregate throughput of the overlay network still leads to maximization of the aggregate throughput?" There have recently been a significant body of research towards designing self-organizing overlay multicast networks by exploiting the inherent selfishness of the peers. These research works can be categorized into two significant strands: *"strategic behavior modeling approach"* [14,21,13,16,22,11,18] and *"non-strategic behavior modeling approach"* [6,19,1–3]. In the former, each peer is treated as a potential game player who seeks to maximize the utility regard to the actions that the other peers do, whereas in the latter each peer seeks to maximize its utility without taking into account the actions of the other peers.

We believe that the aforementioned problem could be investigated using rich theorems of microeconomics. In microeconomics, there exist numerous rich theories that lend themselves to model the behavior of the agents of the economy based on both strategic and non-strategic approaches, depending on the special conditions of the given problem. Each economy consists of three components: Seller, buyer, and commodity. The seller seeks to maximize his or her profit, i.e., revenue minus cost, regard to a predefined level of commodity production. On the other hand, the buyer seeks to maximize his or her utility regard to the budget constraint. Note that both the seller and the buyer are selfish agents in the economy.

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We present a revenue-maximizing monopoly auction framework by leveraging the mathematical tools from the theory of *"mechanism design"* of microeconomics. In this framework, each offered service plays the role of the commodity in the overlay network economy. The buyers in this economy are all the peers either who relay the services to their downstream peers or who are leaf nodes in the overlay multicast tree. Also, the sellers are either the origin servers or the peers who forward the media services to the other peers.

Analoui and Rezvani [1–3] are the first to apply microeconomics-inspired models in the overlay multicast networks. They have presented a non-strategic behavior model by leveraging the concept of *"Walrasian general equilibrium"*. Our study differs from the aforementioned works in the sense that we have used the strategic behavior modeling approach. In our proposed monopoly auction model, the whole bandwidth of service plays the role of the commodity, whereas in the previous works the unit of the bandwidth of the service is considered as the commodity. By leveraging the theory of mechanism design, the overlay economy achieves *"Nash equilibrium" (NE)* which in turn results in optimal bandwidth allocation. It is worth mentioning that in the theorems of auctions, each commodity is treated as an indivisible object, whereas in the models presented by Analoui and Rezvani in [1,2], each commodity is considered to be divisible. A major contribution of our work is that unlike previous works which are based on Walrasian equilibrium, here NE is used as the solution concept. To find the NE, the monopolist sellers must know statistical information about market demand such as the distributions of the buyers and bidding values for the services, whereas Walrasian equilibrium solution does not need to know such private information. To find the Walrasian equilibrium, simply the total demand of each service must be equal to the total supply. To the best of our knowledge, there has been no investigation on designing the protocols for the multi-service multicast overlay networks based on monopoly auctions in the sense that has been defined in the theory of mechanism design of microeconomics.

The remainder of this paper is organized as follows: Section 2 introduces the formal description of the overlay multicast network. Section 3 is devoted to the formal description of the proposed auction mechanism. Section 4 specifies the detailed algorithms of *"join"* and *"leave"* based on the proposed mechanism. Section 5 discusses some theoretical issues relating to scalability, link stress, number of overlay hops, and throughput of the proposed system. Section 6 discusses the performance evaluation of the proposed auction mechanism in the overlay network environment and shows experimental results. Finally, we discuss the related works in Section 7, and conclude in Section 8.

2. Overlay multicast network model

We consider an overlay network consisting of V end hosts denoted by $\mathcal{V} = \{1, 2, \ldots, V\}$. Let us suppose that the overlay network consists of N media services, denoted by $N = \{1, 2, \ldots, N\}$. So, there are N origin servers among V hosts ($N < V$), each serving a distinct type of media service. We denote by $S = \{s_1, s_2, \ldots, s_N\}$ as a set containing N origin servers. Suppose the network is shared by a set of N multicast groups. Any multicast group (multicast session) consists of a media server, a set of receivers, and a set of links which the multicast group uses. The physical links are in fact the physical connections either the router–router connections, or the router–peer connections. Let us suppose that the overlay network consists of L physical links, denoted by $\mathcal{L} = \{1, 2, \ldots, L\}$. The capacity of each link, that is the bandwidth of each physical link $l \in \mathcal{L}$ is denoted by c_l. Fig. 1(a) is an example of the underlying physical topology with eight links ($L = 8$) and two routers.

Fig. 1(b) shows an overlay network consisting of two multicast groups. Here, the solid lines indicate one group and dashed lines indicate the second group. The initial flow in each session originates from a server and terminates in its downstream peers. In this example there is $S = \{s_1, s_2\}$ in which s_1 (node 0) indicates the origin server of one group and s_2 (node 3) indicates the origin server of the other group. Fig. 1(c) shows two multicast trees, each of which has been constructed by joining the peers to the corresponding multicast group. All the nodes, except the leaf nodes, forward the multicast stream via unicast in a P2P fashion.

Since the multicast session $n \in \mathcal{N}$ consists of one origin server and at most V recipients, we can represent its directed graph by a $(V + 1) \times (V + 1)$ *"adjacency matrix"*, denoted by $\mathbf{M}^n$. The $\mathbf{M}^n_{ij}$ element of matrix $\mathbf{M}^n$ denotes the flow that is originated from node i and is terminated in node j. We put $\mathbf{M}^n_{ij} = 1$ whenever there is a flow and zero otherwise. The adjacency matrices corresponding to the example of Fig. 1(c) can be represented as follows

$$\mathbf{M}^1 = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{M}^2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Each multicast session $n \in \mathcal{N}$ consists of F^n unicast end-to-end flows, denoted by set $\mathcal{F}^n$:

$$\mathcal{F}^n = \{f^n_{ij} \mid \exists i, j \in \mathcal{V} : \mathbf{M}^n_{ij} = 1\}. \tag{1}$$

The flows of each multicast group of Fig. 1(c) can be represented as follows

$$\mathcal{F}^1 = \{f^1_{01}, f^1_{02}, f^1_{24}, f^1_{45}\} \qquad \mathcal{F}^2 = \{f^2_{32}, f^2_{34}, f^2_{46}\}.$$

Here, the number of unicast end-to-end flows of sessions 1 and 2 are $F^1 = 4$ and $F^2 = 3$, respectively. Each flow f^n_{ij} of the multicast group n passes a subset of physical links, denoted as follows

$$\mathcal{L}(f^n_{ij}) \subseteq \mathcal{L}. \tag{2}$$

From Fig. 1(b), one can identify the links from which the flows f^1_{24} and f^2_{34} pass through as following:

$$\mathcal{L}(f^1_{24}) = \{l_3, l_5, l_6\} \qquad \mathcal{L}(f^2_{34}) = \{l_4, l_5, l_6\}.$$

For each link l, we have

$$\mathcal{F}^n(l) = \{f^n_{ij} \in \mathcal{F}^n \mid l \in \mathcal{L}(f^n_{ij})\} \tag{3}$$

where $\mathcal{F}^n(l)$ is the set of flows which belong to multicast group n and pass through link l. Fig. 1(b) shows the flows of multicast groups 1 and 2, namely $\mathcal{F}^1(l_6)$ and $\mathcal{F}^2(l_6)$, passing through l_6.

$$\mathcal{F}^1(l_6) = \{f^1_{24}, f^1_{45}\} \qquad \mathcal{F}^2(l_6) = \{f^2_{34}, f^2_{46}\}.$$

Each flow $f^n_{ij} \in \mathcal{F}^n$ in multicast group n has a rate x^n_{ij}. Also we show the set of all downstream peers of each overlay node i in multicast group n by $Chd(i, n)$. In fact, the set $Chd(i, n)$ contains all children of node i in multicast group n. This set is expressed as follows

$$Chd(i, n) = \{v \in \mathcal{V} \mid \mathbf{M}^n_{iv} = 1\}. \tag{4}$$