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Optimizing revenue for bandwidth auctions over networks with time reservations

Pablo Belzarena [a,*], Fernando Paganini [b], Andrés Ferragut [b]

[a] Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay
[b] Facultad de Ingeniería, Universidad ORT, Montevideo, Uruguay

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ABSTRACT

This paper concerns the problem of allocating network capacity through periodic auctions, in which users submit bids for fixed amounts of end-to-end service. We seek a distributed allocation policy over a general network topology that optimizes revenue for the operator, under the provision that resources allocated in a given auction are reserved for the entire duration of the connection.

We first study periodic auctions under reservations for a single resource, modeling the optimal revenue problem as a Markov decision process (MDP), and developing a receding horizon approximation to its solution. Next, we consider the distributed allocation of a single auction over a general network, writing it as an integer program and studying its convex relaxation; techniques of proximal optimization are applied to obtain a convergent algorithm. Combining the two approaches we formulate a receding horizon optimization of revenue over a general network topology, leading to a convex program with a distributed solution. The solution is also generalized to the multipath case, where many routes are available for each end-to-end service. A simulation framework is implemented to illustrate the performance of the proposal, and representative examples are shown.

1. Introduction

The possibility of auctioning bandwidth in real time has been considered by many authors [8,10,14,17,22,23], with a variety of applications: diffserv, access control, 3G cellular access, VPNs, etc. Much of this work has focused on game-theoretic considerations, in particular on providing incentives for bidders to reveal their true utilities. The standard theory of auctions [13] provides these mechanisms for the auctioning of a single resource, but it is far more challenging to extend them to a general network topology. Most proposals in this regard require the user (or a broker entity acting on his/her behalf), to place separate bids for internal resources of the network. In particular, the Progressive Second Price (PSP) mechanism of [14] requires each player to coordinate bids at the different nodes on its route, so that each node may run an auction with the allocation and pricing rules of the single resource case. PSP has a long convergence phase, which is improved by a *multibid* method in [17]; however, the latter mechanism only applies to tree topologies. Another approach to bandwidth auctioning for multicast trees or VPNs is proposed in [8], based on Dutch auctions. The mechanism assumes that users interested in a path would try to reserve bandwidth by placing bids simultaneously for all constituent links.

In this paper we argue that to have practical impact, a bandwidth auction requires a simpler user interface: the consumer should submit a bid for an entire end-to-end service, oblivious of the internal topology. It is the operator's problem to decide which of these bids to accept and how to accommodate the aggregate service within the available network capacity. Furthermore, a more natural

* Corresponding author.
E-mail addresses: belza@fing.edu.uy (P. Belzarena), paganini@ort.edu.uy (F. Paganini), ferragut@ort.edu.uy (A. Ferragut).

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objective than incentive compatibility is revenue maximization for the operator that offers this end-to-end service. As one possible deployment scenario to make the discussion concrete, consider the Service Overlay Network (SON) architecture [11], where an overlay operator has leased tunnels between a set of service gateways located in domain boundaries, and auctions a service of high-quality (e.g. video-on-demand) over this infrastructure, with the objective of obtaining revenue.

Another important aspect of the problem that has not been satisfactorily addressed in previous work are intertemporal considerations. Most references cover a one-shot auction where bids for the entire duration are known initially. References for multi-period auctions (e.g. [22]) allow future bidders to compete with incumbent ones, albeit given the latter some advantage. This is not an attractive condition for our intended applications. Consider for example selling video-on-demand content about 100 min long, in auctions every 5 minutes. A consumer will not purchase the service if he/she faces the risk of losing the connection close to the end of the movie. In this paper we impose the condition that once bandwidth has been allocated in an auction, the successful bidder has a *reservation* for the duration of his/her connection. This means that the operator must assume the risk of future auctions, which makes the maximization of revenue a stochastic dynamic optimization problem.

Both of the above aspects (general network topology, time reservations) lead to optimization problems of high complexity, on top of which we add the requirement of a distributed solution. Rather than an exact solution, we develop in this paper a series of tractable methods that approximate the optimal revenue objective. We begin in Section 2 with auctions of a single resource (single link capacity) with time-reservations, a problem that we formulate as a Markov decision process (MDP) [1,20]. We introduce a receding horizon approximation that is able to capture the dynamic component of the problem in a tractable way, and validate it by simulation. Next, we turn in Section 3 to the network aspect, formulating the allocation of a one-shot auction as an integer program; by recasting this problem in the language of Network Utility Maximization (NUM) [6,12], we develop a natural relaxation that has a distributed solution; convergence is obtained through the application of a proximal optimization method [5,15].

In Section 4 we combine the previous approaches to formulate a receding-horizon optimization of revenue for multi-period auctions over a distributed network, which again is formulated as a variant of a NUM problem, solved in relaxed form through a proximal method. We develop in this case a distributed implementation of the algorithm, and exhibit its performance in a series of simulation examples that progressively include more realistic situations. Finally, in Section 5 we consider multipath optimization, where end-to-end services can be offered through multiple routes inside the network; we show how to extend the methodology to this case. Conclusions are given in Section 6.

This article is an extension of our conference papers [2,3]. One main enhancement included here is the proximal approximation method to ensure convergence of our distributed algorithms with non-strictly concave utilities. Also, the entirety of Section 5 on multipath auctions is new material.

2. Periodic auctions of a single resource with time reservations

We consider first an auction for the capacity of a single resource, the bandwidth of one link, postponing the consideration of network topology. The focus here is the temporal dimension: auctions are held periodically, based on bids collected for a period of time of duration T. When each auction closes, the provider decides which bidders are allocated capacity, which is subsequently *reserved* for a service duration that may exceed T. In particular, when the next auction occurs, new bidders are not allowed to displace incumbent users. The objective is to find an allocation policy that maximizes revenue of the seller over time, under the assumption that users pay their bid upon admittance to the service, a first-price auction. Later on we discuss strategic implications.

We establish some notation. Let σ be the bandwidth requirement of the single service being auctioned; the provider has capacity c to auction. In this section we normalize $\sigma = 1$, and assume c is an integer.

The discrete time index k defines the auction at time kT, for which the seller has received N^k bids, ordered as

$$b^{k,(1)} \geqslant b^{k,(2)} \geqslant \cdots \geqslant b^{k,(N^k)}.$$

The result of the auction is a capacity allocation a^k to a set of highest bidders, yielding a revenue of

$$U_{b^k}(a^k) := \sum_{i=1}^{a^k} b^{k,(i)}. \quad (1)$$

This function $U_{b^k}(\cdot)$ is defined above for integer values of a^k; we will also apply this notation to the function of $a^k \in \mathbb{R}$ defined by linear interpolation, and constant above N^k. This piecewise linear function is increasing and concave in a^k, since bids are decreasing.

If we were considering a single auction of the capacity c, clearly the optimal revenue decision would be to sell as much as possible, $a^k = \min\{c, N^k\}$. However, the occurrence of periodic auctions and reservations across multiple periods complicates the decision significantly, as discussed next.

2.1. Optimal allocation as a markov decision process

The long-term optimal revenue problem is posed in terms of a stochastic model for the bidding and duration processes. The model assumptions are now described:

- **Distribution of bids.** We assume bids are drawn independently from a continuous probability distribution. For the theory to follow, we will assume the distribution is known; in Section 4.2 we show how it can be learned from past observations.