# Hierarchical Package Bidding: Computational Complexity and Bidder Behavior

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## Extended Abstract

Hierarchical package bidding (HPB) is the first combinatorial auction format used by the US Federal Communications Commission (FCC) for the sale of spectrum. This can be considered a major breakthrough after more than 14 years of discussion on the design of a combinatorial auction for the FCC. In HPB, all licenses are prepackaged in a hierarchical manner and bidders can only submit OR-bids on packages defined in this hierarchy, which leads to linear time complexity of the winner determination. A strength of HPB and a reason for the choice by the US FCC was this computational simplicity when determining the allocation and ask prices. While HPB allows more expressiveness than the Simultaneous Multiround Auction (SMR), the number of allowed package bids is restricted by the hierarchy imposed on the items by the auctioneer. Obviously, if the hierarchy does not fit the bidders' preferences, the OR bidding language of HPB can cause exposure problems as in a simultaneous auction with complementary valuations, and similar equilibrium strategies apply as in SMR. So far, the analysis of HPB is limited to a set of laboratory experiments conducted by Goeree and Holt.

We extend this analysis in two ways. First, the OR bidding language can pose a severe limitation in many applications. The auctioneer or bidders might want to use an XOR bidding language or use various other side constraints in the winner determination. Such constraints can limit the number of items a single bidder is able to win or the overall budget that a bidder will spend. Side constraints are important in many domains. Spectrum auctions, which have been the driving application for much research in this area, regularly face spectrum caps. In procurement applications, side constraints are the rule rather than an exception. We analyze the computational complexity of HPB with additional constraints and show that HPB loses its computational virtues and the winner determination problem becomes $\mathcal{NP}$-hard as soon as such constraints are present.

Second, we try to understand behavioral reasons for inefficiency of HPB. We conducted another series of lab experiments. In one set of experiments, we replicated the experimental design with global synergies introduced by Goeree and Holt. In another set of experiments, we conducted an experiment with local synergies. One prominent example of such synergies are spectrum auctions with

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regional licenses as in the USA. The differences in efficiency and revenue in our experiments is statistically significant to the ones conducted by Goeree and Holt, but it is still small. However, we find several interesting reasons for these inefficiencies both in the global and local value model relevant to regulators and auctioneers. For example, HPB can increase the coordination problem of smaller bidders and favor the national bidder who is interested in almost all items. Reasons include jump bids which are bids above the required bid prices and activity rules employed, as well as exposure problems for small bidders in HPB. We also monitor which packages were evaluated by bidders, and when they evaluated these packages. Interestingly, we find that most bidders preselect a small number of packages and fail to evaluate new ones throughout the auction in spite of sufficient time and monetary incentives. This preselection actually accounts for most of the inefficiency, which we find in HPB and might be an explanation for inefficiencies in combinatorial auctions in general.

**Keywords:** combinatorial auctions, computational complexity, bidding languages, bidder behavior.