A simulation-based approach to bidding strategies for network resources in competitive wireless networks

Fernando Beltrán and Matthias Roggendorf

University of Auckland Business School
7 Symonds Street, Auckland, New Zealand
{f.beltran,m.roggendorf}@auckland.ac.nz

Abstract. We introduce a simulation-based approach to the problem that mobile users may face in a multi-provider environment when seeking to satisfy their demand for bandwidth; if they are allowed to satisfy their individual demands by aggregating shares from two or more providers the problem becomes one of resource allocation in a competitive market. We use the Progressive Second-Price auction at each provider, exploring the properties of three bidding strategies. Simulations aim at learning whether the auction converges at each seller when bidders, either make coordinated or non-coordinated decisions among auctions, or complement already secured shares by bidding at other auctions. Aggregate measures of welfare and sellers' revenue are obtained for each simulation run.

1 Introduction

The introduction of IP for packeting, routing and transportation of digital information in data communication networks has opened up a tremendously broad range of possibilities for the creation of innovative services. Wireless networks are no exception to this trend; traditional cellular telephony providers as well as new entrants are already operating IP-based services in networks of the second (2G) and third (3G) generation. The next generation of wireless networks (NGWN), which currently emerge from cellular network standards and wireless data communications networks, promises to be an all-IP ubiquitous network, capable of providing multiple service types with guaranteed quality of service [1].

IP-based wireless networks introduce new network management paradigms, especially with reference to resource allocation. When resource allocation is considered, it is convenient to break the problem up in accordance to its particular definition and design on each layer of the Internet protocol. If a whole approach to resource allocation is to be attempted, two functions need to be considered: *subscription* and *access*. Both describe stages in the transaction between provider and users when purchasing services from a network. A network provider hands in a contract to a consumer by which a commercial relation is begun; consumers count as subscribers to the network. When subscribers need to activate their connection, they must get access to network resources - for instance, bandwidth.

One of the most exciting implications of such technological progress is the possible erosion of the subscription paradigm. As new providers step into the market for individual consumers, the flexibility provided by more efficient and adaptive networks will make it possible for consumers to demand access from a network where no previous subscription contract had been signed. Therefore, networks will have to compete for consumers "on-the-spot". The central issue of this paper is the modelling of a new resource allocation scenario implied by NGWN. In such a scenario, two or more wireless operators serving a common service area will see mobile users demand connection to their networks. We assume that a competitive wireless multi-provider setting may well be endowed with a competitive access bidding mechanism. Therefore, any wireless provider herein considered is assumed to solve its resource allocation problem at the access level using an auction.

Pricing schemes consisting of a flat fee provide wrong incentives for resource utilization. Such schemes risk rendering the network inefficient as users, unaware of their impact on the efficient utilization of resources, tend to behave as the exploiters of a common resource with the known consequences of over consumption known as 'the tragedy of the commons' [2]. When a limited resource, such as bandwidth, in an access link is consumed on a flat-fee payment basis, the main concern for the operator is congestion. If the network keeps admitting new connections above a certain level, the consequent degradation of the quality of service will make users turn away. This is especially true in wireless access networks as, despite the development of new technologies, capacity is still of concern. Therefore, a mechanism is needed that will charge an amount that aims to compensate for the effect that any user has on others and, at the same time, provide disincentives for over-utilization.

This paper is organised as follows: in Section 2 the PSP auction is revisited; in Section 3 we formulate the main problem studied here; in Section 4 we introduce three bidding strategies and in Section 5 we present the results of extensive simulation trials. Conclusions and future research are discussed in Section 6.

2 The Progressive Second-Price Auction

The literature on the design of pricing mechanisms for congestion control and charging mechanisms presents an interesting application of the Vickrey auction [3]. When considered as a divisible amount, bandwidth becomes a 'divisible' object to be allocated among agents searching for network resource through a competitive bidding process. Semret [4] introduces the Progressive Second-Price (PSP) auction, an application of the Generalised Vickrey (GV) auction, to allocate divisible objects, in which a bidder submits a quantity and a price to an auctioneer who, in return, will tell the bidder how much of the requested quantity he will get and the overall cost per time unit to be charged.

The Vickrey-Clark-Groves (VCG) mechanism is an incentive-compatible mechanism with additional properties: VCG is efficient (i.e., it maximises social welfare) and individually rational (i.e., it guarantees that any agent joining the mechanism derives a non-negative utility) [5]. The PSP auction inherits all these properties.

Let us suppose the seller's network has a capacity of Q units. In a PSP auction any user submits information consisting of two values: the desired share of the total resource q_i and the price p_i he is willing to pay for it. The auctioneer allocates a share a_i of the resource to player i at the cost c_i. The allocation rule assigns player i bandwidth a_i equal to the minimum value between his capacity bid, q_i, and the remaining capacity after all those capacity bids, q_k, whose prices beat $i's$ bid ($p_k \geq p_i$) are subtracted from the total capacity Q to be allocated. In other words, the allocation rule is:

$$a_i(s) = q_i \wedge \left[Q - \sum_{p_k \geq p_i, k \neq i} q_k \right]$$

and s represents the set of bids by i, denoted as s_i and by the rest of the players, denoted as s_{-i}. The payment by any agent i is a weighted average of the (unit) prices offered by the other agents; each weight is the incremental capacity from including j in the auction. The pricing rule can be written as:

$$c_i(s) = \sum_{j \neq i} p_j \left[a_j(s_{-i}) - a_j(s_i; s_{-i}) \right]$$

Events such as a new user attempting to join the network or another user leaving trigger the search for a new equilibrium and prompt users to start the submission of new bids. In order to guarantee the convergence of the algorithm a bidding fee ϵ has been introduced to let bidders change their bids only when the gain in net benefit is large enough. This is expressed in [4] as a modified concept of equilibrium known as ϵ-Nash equilibrium. From a technical perspective, the algorithm produces a minimum of signalling overhead since only two values have to be submitted.

Several extensions and modifications of PSP have been proposed. The most prominent one is the multi-bid auction by Maillé and Tuffin [6]. Instead of sending single bids in each auction round a player submits his demand function, which is actually a stepwise, descending price schedule, to the auctioneer. This avoids the convergence phase to reach equilibrium.

3 Procuring resources in a multi-provider setting

We are concerned with the following problem: bidders may participate in two or more auctions occurring simultaneously. At each auction, network capacity or bandwidth is being offered. Each bidder is seeking to win an amount, which he can procure from multiple sources in any combination. We would like to explore what constitutes an optimal bidding strategy for a bidder. Being incentive-compatible, PSP will be considered as the mechanism implemented at each seller. In the problem herein considered, consumers seek bandwidth to fulfil their needs for communication services. Two or more providers may provide access to the users' mobile terminals through the auctioning of bandwidth. Auctions occur simultaneously. Each user is seeking to win an amount of bandwidth, which he could procure from one or more sources in any combination.

In the case of several multi-unit auctions with users requesting one or more objects, the literature does not provide a solution in which direct mechanisms at each seller elicit truthful (incentive-compatible) bids from the bidders when bidders are allowed to satisfy their demands by adding shares from several sellers. Some progress has been done when studying the problem faced by the bidder when each of two auctioneers has a single unit to auction and both use either a first-price or a second-price auction [7].

Let us assume that a bidder needs a given amount (share) of a divisible good and there are two sellers which can provide the good. The objective of each bidder participating in the market is to maximise the individual utility derived from all auctions. We cannot assume beforehand that each bidder will be motivated to report truthfully to each auctioneer in the marketplace. When a user needs to procure a resource from a divisible resource being auctioned, he faces the problem of finding an adequate bidding strategy. In one line of analysis we must consider the bidder who seeks to source from one provider as opposed to sourcing from several providers. The former situation might, for example, apply to mobile users which are restricted in terms of hand-over or handset capabilities. In the latter, users may be able to bundle resources from several wireless providers. Bundling of resources can, for example, be used by stationary users with adaptive services to increase bandwidth for data transfers or video streaming.

4 Bidding strategies

To explore possible bidding strategies for both, single-source and multiple source bidding agents, different policies have been defined and implemented in the simulation environment. We restrict our attention to sequential bidding strategies in which agents submit only one non-zero bid to one auction. A exception is the *BidAll* strategy, in which agents submit bids to all auctions simultaneously.

BidAll: With this bidding strategy bidders behave as if they were independently bidding on both auctions. No coordination of submitted bids takes place and agents bid on both auctions. Since bids are not coordinated this strategy is not truthfully revealing an agent's preferences to the system. If a bidder receives resources from several providers in equilibrium, he risks paying more than its marginal value when adding up resources from all auctions. In this case, a bidder would pay a negative rent for the resources obtained and would be better off by not bidding at all. The simplified algorithm for *BidAll* is given as Algorithm 1.

UtilityBased: The *UtilityBased* bidding strategy coordinates bidding on several auctions by comparing the utility expected to be received and selecting the auction with the highest utility in each period.[1] Only one new bid is submitted in each period. Bids from previous periods stay active but might be overbid

[1] We define the expected utility as calculated from the bid to be submitted and the expected utility as the consumers welfare obtained from the share of resources won in the last round

Algorithm 1 *BidAll* Bidding Strategy

```
loop
    Receive results from all active auctions
    for all active auctions do
        Generate a truthful reply
        if truthful reply can be generated then
            send new bid to auction
    sleep for 1 second
```

by other bidders in the following rounds. With this bidding strategy a bidder reduces his risk of overbidding since he only sends one truthful reply in each period. However, in equilibrium, bidders can potentially end up with resources allocated from more than one auction as bids from previous periods might be still winning bids. An algorithmic description of *UtilityBased* is presented as Algorithm 2.

Algorithm 2 *UtilityBased* Bidding Strategy

```
VARIABLES: highest_auction
loop
    Receive results from all active auctions
    for all active auctions do
        if truthful reply can be generated then
            if expected utility from truthful reply > utility[highest_auction] then
                Save current auction index in highest_auction
            else if received utility > utility[highest_auction] then
                Save current auction index in highest_auction
    if for highest_auction a truthful reply can be generated then
        send new bid to highest_auction
    sleep for 1 second
```

ComplementaryUtility: This bidding strategy implements the idea of "dividing up" the demand for bandwidth between auctions. In each step the auction with the highest utility is determined and a new bid is sent out. Other auctions with lower utility are seen as additional sources to 'complement' the resource allocation from the highest auction. But instead of risking to overbid at other auctions, a bidder adapts his demand function by subtracting the quantity expected on the leading auction. This lowers the chances of winning on other auctions but prevents overbidding situations since the bidder is truthfully revealing his value under the assumption that results on the first auction can be achieved. Figure 1 shows how the demand functions for subsequent auctions are implemented. If an agent has obtained q_1 from the auction with the highest utility it can form a new valuation function beginning at $q_1, v(q_1)$, which can be used for other auctions, complementing the already obtained resources. Algorithm 4 depicts the simplified algorithm for *ComplementaryUtility*.

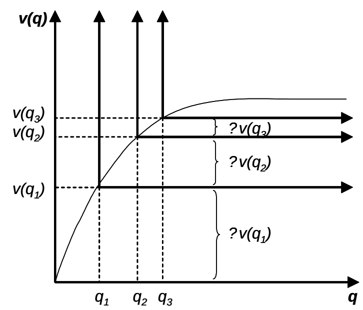


Fig. 1. Definition of valuation functions for subsequent auctions

Algorithm 3 *ComplementaryUtility* Bidding Strategy

VARIABLES: *sorted_auction_list[ ], i*
loop
  Receive results from all active auctions
  for all i = active auctions **do**
    if truthful reply can be generated **then**
      Sort result into *sorted_auction_list[i]*
  for all i = auctions in *sorted_auction_list[ ]* start with the highest **do**
    if for *sorted_auction_list[i]* a truthful reply can be generated **then**
      send new bid to *sorted_auction_list[i]*
      form a new valuation function with remaining utility
  sleep for 1 second

5 Simulation Approach

We employ simulation as the main research methodology. Simulation allows us to translate the defined bidding strategies into software code and to directly observe equilibrium results with several settings and with different input parameters. Since bidding within the PSP context happens in multiple rounds we are also able to observe the bidding behaviour over time as well as the progression of aggregated values such as provider revenue or overall social welfare.

While in principle it is possible to use mathematical modelling to obtain exact results in terms of convergence and equilibrium results, we believe that because of the complexity introduced by the competitive setting and the ability of bidders to obtain results from multiple sources, closed solutions can only be expected in a very few and specialised cases. Therefore, we see simulation as a tool for discovering the emergent properties of the developed bidding strategies and to apply a more rigorous analytical analysis in a second step.

Additionally, simulation allows us to gain a richer picture of the proposed bidding strategies, which are impossible to analyse with alternative research methods. For example, we can introduce an additional bidder when a market has already come to equilibrium an observe the consequences in terms of convergence time and allocation of resources. For the development of the simulation platform we have made use of the standard development techniques described in the literature (for an overview see e.g., [8]). This especially applies to the model verification after the basic implementation and the design of the simulation experiments.

The general simulation platform, which has been developed with the objective of reusability and openness toward alternative market mechanisms, has been developed in Java using the *Java Agent DEvelopment Framework* (JADE)[2]. JADE provides a middleware concept to set up multiple, independently acting software agents. Each market participant can be modelled as a separate agent entity with a specific behaviour profile. This also allows for the setup of a mixed agent population in which each agent employs a different bidding strategy. The JADE communication protocol provides a simple implementation of agent interaction in form of messages. Additionally, JADE provides a generic discovery service to dynamically identify other agents with certain properties.

A detailed discussion of the simulation architecture and the developed agent ontology can be found in [9].

6 Experimental Results

We have conducted two types of experiments. In the first type of experiments input, parameters are deterministic but due to the timing of events (for example, in which order bids are submitted to the auctioneer), different results can emerge. The second type aims at understanding the dynamic behaviour of the proposed bidding strategies. Users profiles are randomly generated.

We assume that agents use a second-order (parabolic) valuation model of the form

$$\theta_i(q) = \begin{cases} -\frac{\overline{p}_i}{2\overline{q}_i} q^2 + \overline{p}_i q & \text{for all } q \leq \overline{q}_i \\ \frac{\overline{p}_i \overline{q}_i}{2} & \text{for all } q > \overline{q}_i \end{cases}$$

The parameters $\overline{p}_i$ and $\overline{q}_i$ can be interpreted as follows: $\overline{p}_i$ defines the marginal unit price of player i at quantity 0, and $\overline{q}_i$ defines the maximum quantity share a player wishes to win. This type of valuation function has been proposed and substantiated by Semret [4] and simplifies the implementation of the corresponding calculations by the simulator.

6.1 Scenario 1: A five-bidder case with two providers

A very simple setup, in which five agents have access to two providers, is used to demonstrate the basic properties of the three bidding strategies.

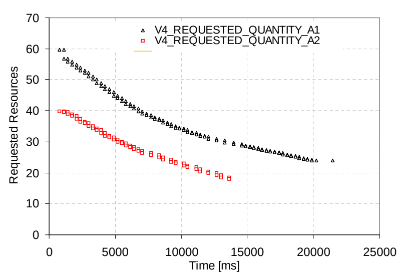
In Scenario 1 two wireless networks and five customers are represented by software agents. All customers have access to both wireless network providers, which offer resources of $Q^{(1)} = 60$ and $Q^{(2)} = 40$, respectively. The factor ϵ has been set to 10 and bidders update their bids every $300msec$. The values of $\overline{q}$ and $\overline{p}$ for each bidder are (90,10), (85,12), (80,15), (70,20) and (65,22).

For each bidding strategy we run an experiment and record the results over time, showing the results obtained by *BidderAgent4* in Figure 2. As expected, with the *BidAll* bidding strategy, bidders reduce their demand on all auctions

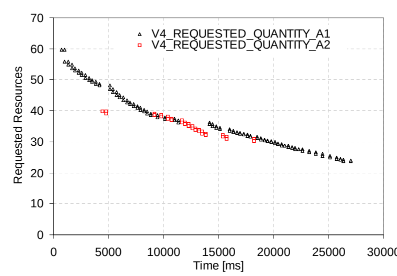
[2] A more detailed description of the JADE environment can be found at http://jade.tilab.com

until equilibrium is reached. The same behaviour can be observed for the *Utility-Based* strategy. However, several steps are undertaken when bidders stay inactive on one auction while bidding on the other auction. This process delays the final convergence to equilibrium.

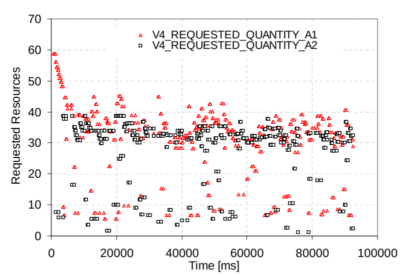
The behaviour of *ComplementaryUtility* differs from both other strategies because no smooth convergence to equilibrium can be observed. Instead, bidders change bids on both auctions erratically depending on their opponents' profiles received from the last round. While a stepwise convergence (bidders start to decrease their bids continuously) can be observed for short time intervals, the strategy is non-converging in general. However, due to the simple setup of the simulation experiment we can observe that the market achieves a ϵ-Nash equilibrium. Since the experiments are conducted in an agent-based simulation environment without central synchronisation, the equilibrium and the convergence process depend on the order of bids submitted. Therefore, results differ in each simulation run.



(a) BidAll



(b) UtilityBased

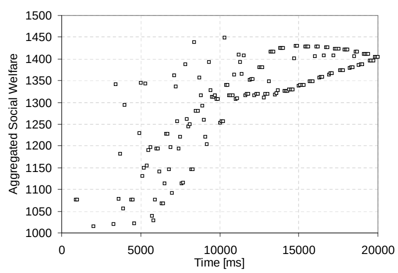


(c) ComplementaryUtility

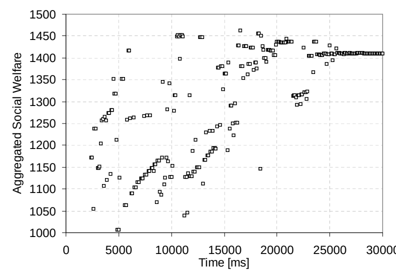
Fig. 2. Requested quantities of *BidderAgent4* over the simulation period with each of the proposed bidding strategies.

In a second experiment we have tested the relation between the factor ϵ and the convergence time to equilibrium. While for the two converging bidding strategies a clear relation between an increasing ϵ and a decreasing convergence time can be observed, the relation for the *ComplementaryUtility* is not obvious.

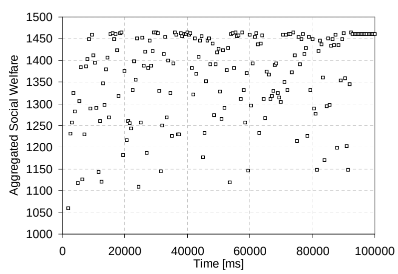
Besides convergence, we are also interested on the performance of the system measured through the aggregated welfare in equilibrium. Aggregated (social) welfare is defined as the sum of the revenue and the consumer surplus for each simulation run and is measured in a fictitious monetary unit. For the given example we can analytically derive the optimal allocation and resulting maximal welfare to be 1465.85. Figure 3 shows the progression of aggregated welfare over time until equilibrium has been reached. It can be observed that with the *BidAll* strategy and the *UtilityBased* strategy the equilibrium reached is not welfare maximising. With an aggregated social welfare of 1459.1 the *ComplementingUtility* strategy reaches an outcome in equilibrium that is within the ϵ-Nash boundaries. For this special case we can therefore conclude that this strategy allocates efficiently.



(a) BidAll



(b) UtilityBased



(c) ComplementaryUtility

Fig. 3. Aggregated social welfare over the simulation period with each of the proposed bidding strategies.

So far, we have kept the allocation of resources between the two auctioneers fixed. In the next experiment we aim at understanding the change in aggregated social welfare when the relative share of resources between providers is gradually changed. For each bidding strategy, 50 experiments were conducted. In each run the distribution of resources between the two providers was changed from $Q_1 = 50, Q_2 = 50$ to $Q_1 = 100, Q_2 = 0$. When the equilibrium at both auctions was reached, the values for revenue and consumer surplus were recorded for all bidders. Figure 4 shows the aggregated social welfare for each possible allocation of resources between the two providers.

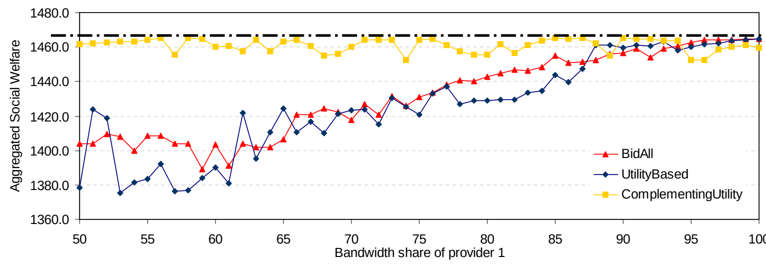


Fig. 4. Aggregated social welfare when shifting resources between auctioneers from [50,50] to [100,0]

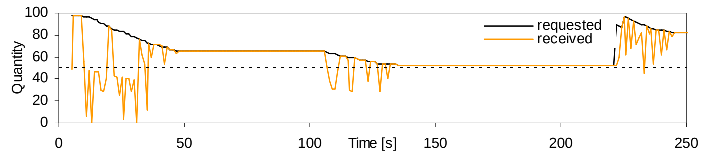
A prominent result is that for the two bidding strategies, *BidAll* and *UtilityBased*, the total welfare generated by different combinations of proportions in which providers supply the access market approaches the maximum as one seller's share becomes larger than the other's. There is some loss in efficiency when the market is equally supplied in comparison to the one-provider situation. The *ComplementaryUtility* strategy produces equilibrium results which are in the defined bounds of the 2ϵ interval. Since agents seem to bid more carefully when using the *UtilityBased* strategy, because they only submit a new bid when it provides a higher utility than the current bid does, we would expect such strategy to improve consumers' surplus over the *BidAll* strategy. However, when providers equally supply the access market, *UtilityBased* yields more revenue to them than *BidAll* does.

6.2 Scenario 2: Bidding behaviour in a complex scenario

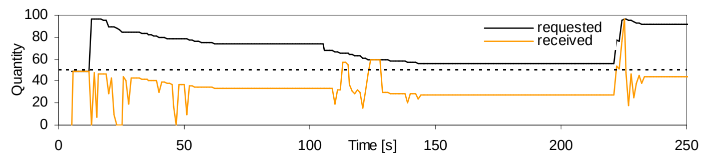
For the second simulation scenario we define a more complex setting and randomly create agent profiles and locations. We can summarise the setup as follows:

- Two network providers are running running four access points (AP) each to cover an area of 500 by 500 units. Access points are represented by agents offering network resources. The entire area is covered by both providers. Each access points offers a capacity of $Q = 300$.
- 100 user agents are randomly distributed over the service area. All users have a constant maximum demand of $\bar{q} = 50$ and a maximum marginal unit price $\bar{p}$ generated from a uniform distribution on the interval $[10, 20]$. All agents have access to only one provider, which has been randomly selected. If a user can access more than one AP it selects the AP closest to him.
- 70 agents initially request service. 30 agents join the market place at $t = 100sec$. 50 randomly selected agents leave at $t = 220sec$.

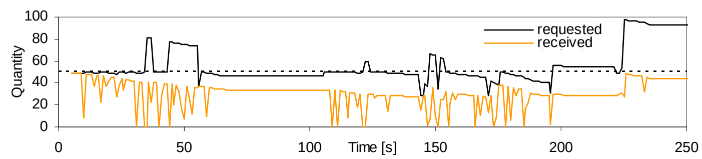
– One agent with $\bar{q} = 50$ and $\bar{p} = 15$, which has access to both providers, is located at position $(200, 200)$. In three different experiments he uses the *BidAll*, *UtilityBased*, and *ComplementaryUtility* strategy, respectively.



(a) BidAll



(b) UtilityBased



(c) ComplementaryUtility

Fig. 5. Summed requested and received quantities for the bidder with access to two providers under the three bidding strategies.

In all experiments we record the requested and received resources for this agent. Figure 5 shows the results. With the *BidAll* strategy the agent is able to acquire the the highest amount of resources. However, since bids to the different auctions are not coordinated, he also receives more than his actual demand for some time periods. While the total price may not be above his willingness-to-pay he captures units of the resource, which bring no additional value to him.

With using the second bidding strategy we observe that while overall requested quantity is comparable to the BidAll strategy. However, since the player is coordinating his bids, the received quantity is not larger than his maximum demand for longer periods of time. This is because a bidder may still have a valid bid in an auction but is not updating it any more because resources on other auction places have become more attractive.

With the *ComplementaryUtility* strategy the player bids much more cautiously. The received quantity always stays below the maximum demand. Compared to the other two strategies the identification of equilibrium is erratic and the process to get to a stable allocation takes much longer. This is especially true for the second time period, when a total of 100 players are present in the market.

7 Conclusion

In this paper we have presented different possible bidding strategies if players are allowed to satisfy their individual demands by aggregating shares from bidding for resources at two or more auctions. We have endowed each seller with the Progressive Second-Price auction, which provides a rich framework, as the auction implemented at a single seller is efficiency and incentive-compatible. Simulations aim at learning whether the convergence properties of PSP hold at each seller when bidders either make coordinated (*UtilityBased* strategy) or no coordinated decisions among auctions (*BidAll* strategy), or complement their already won share at a given auction by bidding at other auctions if they need to (*ComplementaryUtility* strategy). Results provide an idea on how social welfare is affected by the aggregated behaviour of the bidders. Also, we can observe how the different bidding strategies influence the bidding behaviour of a single bidder, when endowed with the option of having access to multiple service providers.

References

1. Berezdivin, R., Breinig, R., Topp, R.: Next-generation wireless communications concepts and technologies. IEEE Communications Magazine **40**(3) (2002) 108–16
2. Hardin, G.: The tragedy of the commons. Science **162** (1968) 1243–48
3. Vickrey, W.: Counterspeculation, auctions and competitive sealed tenders. Journal of Finance **16** (1961) 8–37
4. Semret, N.: Market mechanisms for network resource sharing. PhD thesis, Columbia University, Center for Telecommunications Research (1999)
5. Krishna, V.: Auction theory. Academic Press (2004)
6. Maillé, P., Tuffin, B.: Multi-bid auctions for bandwidth allocation in communication networks. In: the proceedings of the 23rd IEEE Infocom Conference, Hong-Kong, China. (2004)
7. Zeng, D., Cox, J., Dror, M.: Coordination of purchasing and bidding activities across markets. In: the proceedings of the 37th Hawaii International Conference on System Sciences. (2004)
8. Woolridge, M.J.: An introduction to multiagent systems. New York: J. Wiley (2002)
9. Roggendorf, M., Beltran, B., Gutierrez, J.: Architecture and implementation of an agent-based simulation tool for market-based pricing in next-generation wireless networks. In: the proceedings of TridentCOM 2006, 2nd International IEEE/Create-Net Conference on Testbeds, Barcelona, Spain, March 1-3. (2006)