A Fair Mechanism for Recurrent Multi-unit Auctions

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Abstract. Auctions are a good tool for dealing with resource allocation in multi-agent environments. When the resources are either renewable or perishable resources, a repeated auction mechanism is needed, in what is known as recurrent auctions. However, several problems arise with this kind of auction, namely, the resource waste problem, the bidder drop problem, and the asymmetric balance of negotiation power. In this paper we present different mechanisms to deal with these issues. We have evaluated the mechanisms in a network bandwidth allocation scenario, and the results show that the proposed mechanisms achieve higher benefits for the auctioneer, while also providing a fairer behavior.

1 Introduction

Auctions are becoming popular within the field of Artificial Intelligence due to its usefulness for resource allocation on competitive multi-agent systems [3], and its multiple types suitable for a wide range of situations.

However, auction mechanisms may have problems in some domains when renewable and perishable or consumable resources are being auctioned as pointed out by [8]. On one hand, renewable resources means that the auctioneer offers the resources every time they become free (when the time of the contract expires). Then the auctioneer needs to allocate the resource to bidders again. On the other hand, perishable resources cannot be stored or left unused. That is, often, there is a free disposal condition in which the auctioneer can leave the resource unassigned if the benefit is maximized. Then, in a next auction, the auctioneer could re-sell the remaining resource. However, when the resource is perishable, this situation cannot happen. Related to these issues is the allocation of resources to bidders for specific time only [7]. In this domain, short-term contract is often used in those markets.

In these cases in which renewable and perishable resources are managed, the auction is repeated several times, in what has been called *recurrent* auction. A recurrent auction is an auction where the bidders are continuously competing for the resources. These kind of auctions have received little attention [6, 12, 7], but they are gaining importance, since there are many applications where this recurrence takes place, such as e-service oriented marketplaces.

Our research concerns these kind of auctions. Particularly, we are interested in recurrent multi-unit single-item auctions. On one hand, in single-item auctions an item is auctioned at a time (conversely to combinatorial auctions in which several items can be auctioned together). On the other hand, multi-unit auctions means that there is more than one unit of each item being auctioned. A typical example of the applicability of this kind of auctions in the e-service domain is the provision of network bandwidth. There is a single item to be sold: the network capacity, and there are several units of the item (depending on the capacity of the connection). Another example regarding natural resource allocation, is the CO_2 emissions. In this scenario, there is a single item, the CO_2 capacity, that is divided into identical units called CO_2 credits [2].

In this paper we present various recurrent multi-unit single-item auction mechanisms to improve the final outcome of the auctioneer by getting fair or egalitarian solutions. The first mechanism is based on assigning priorities to the bidders; the second mechanism on defining variable reservation prices to pay for the use of the resource, and the third mechanism is a combination of the two previous ones. We experimentally show how the latter mechanism outperforms the former and the previous approaches found in the literature.

The paper is organized as follows first, we provide some basis on recurrent multi-unit single-item auctions (or recurrent multi-unit auctions for short) in Section 2. Next, in Section 3, we describe the new auction mechanism we propose. Then, we continue by describing our experimental scenario in Section 4 and explaining the results obtained in Section 5. Finally, we end with some related work and conclusions.

2 Issues in Recurrent Multi-unit Auctions

In a recurrent multi-unit auction, the auctioneer has some goods to be sold periodically. Then, auctions are repeated with the same bidders through time. In each auction, the auctioneer agent sends a message to all the bidder agents, offering the different units of the item to be sold. Then, the bidders send back to the auctioneer their bids, containing the price they would pay for a single unit of the item, sending as many bids as units required. Next, the auctioneer decides to which agents it will sell the available units of the item. In this process, three main components are distinguished:

- Bidding policies: how each agent decides the price it would pay
- Market clearing or winning determination algorithm: how the auctioneer selects the agents that win the units of the item (or selects the winning bids).
- Pricing mechanism: how the auctioneer decides the price to be paid for the winners

Our research is concerned in the second one. The market clearing or winning determination algorithm poses an optimization problem to the auctioneer that tries to maximize its benefits [4].

If there is the free disposal condition, then the auctioneer can keep some of the units if the benefit is higher. However, this free disposal condition has to be minimized when dealing with perishable resources, as it can produce what is known as the *resource waste problem.* Other problems related to recurrent auctions that should be tackled in the market clearing mechanism are the *bidder drop problem* and the *asymmetric balance of negotiating power.*

2.1 Resources Waste Problem

Resources can be either static or time-sensitive. Static resources do not change their properties during a negotiation process [3]. On the other hand, a time-sensitive resource [7] is consumable or perishable. A resource is consumable if it gets worn out by constantly using it. For example, fuel is a consumable resource. A resource is perishable, if it vanishes or loses its value when held over an extended period of time. For example, network bandwidth is a perishable resource since the bandwidth not used is not accumulable for the future.

The perishable resources, present in many real-world scenarios, cannot be stored in warehouses for future sales; if the resources are not allocated they lose their value or vanish completely. This is known as the *resource waste problem* in recurrent auctions, since if the auctioneer does not sell the resource in a round, it cannot sell it in the next round. On the other hand, it cannot give the resource for free. So a trade-off on the resource usage and the benefit of the auctioneer should be appropriately handled.

2.2 Bidder Drop Problem

This problem occurs when bidders participating in many auctions are always losing. They could decide to leave the market, since they are not getting any profit. This has bad consequences for the auctioneer: the reduction on the number of bidders gradually decreases the price competition, because the probability of winning increases for the remaining bidders. Hence, their attempts to decrease bid prices without losing the winning position will be successful, causing the overall drop of bid prices.

In order to avoid, or somehow decrease, the bidder drop problem, the recurrent auction process should have some degree of *fairness.*

2.3 Asymmetric Balance of Negotiating Power

In most of the traditional auction mechanism, the bid prices in an auction are dependent only on the customer's willingness to pay for the traded goods. This means that only the intentions of customers, but not of the auctioneer, are reflected in the auction winning prices [6]. At long run, the effect of this problem causes the collapse of the auction. For example, let us suppose that initially there are N bidders. A third of them, are poor and bid 1€; while the other two thirds are richer and pay some amount over 5€. After several rounds, the richer agents start lowering the price up to 3€, while the poor agents rise their bids up to 2€. At the end, the richer agents are the winners with a price close to the poor agents. In this case, the richer bidders have the power of fixing the price, not the auctioneer. In a recurrent auction, these prices can even go under the poor prices, if the poor agents have dropped out of the market.

3 Mechanisms for Fair Auction Clearing

In the recurrent auction mechanism a fair solution means that at long term, all of the participants accomplish their goals in the same degree, independently of their wealth. The inclusion of this fairness can be somewhat acting against short-term optimality, since the result of an auction may differ from the optimal solution if a suboptimal solution is fairer. However, its mid or long-term effect produces an increase of auctioneer benefits, since it maintains the interest of bidders in continuing in the auction process [6].

We propose three different mechanisms based on the use of priorities and variable reservation prices for reaching fair solutions and solve the problems of recurrent auctions. The first mechanism is the priority auction that solves the resource waste and the bidder drop problem, the second one is the customizable reservation price auction that solves the asymmetric balance of negotiation power and the bidder drop problem and finally the last one is the customizable reservation price auction with priorities that achieve to solve the three problems.

3.1 Priority Auction (PA)

This mechanism takes into account the history of each agent in previous auctions. Each agent is assigned a *priority* value depending on the number of won and lost auctions. Thus, priority is defined in *[0,1]*. The more number of lost auctions, the higher the priority. The priority values are updated after each auction is finished, and they are used for clearing the next auction. The clearing algorithm could use them in very different ways: they could be transformed into new constraints to be satisfied by the solution, or directly designate the set of winning agents, among others.

Since the history of the agents in a recurrent auction scenario is long, a time window could be used to calculate the priorities instead. If the time window is very long, then the performance of PA is like the traditional auction (TA) (i.e. the typical auction where winners are the bidders with the highest bid) since the effect of the result of an auction is insignificant when the number of auction is high.

Thus, we propose to use this priority to modify the value of the bids and selects as winners the highest modified bids. More precisely, given a bid value v_i of an agent with priority w_i, a new bid valuation is computed as:

$$v'_i = f(v_i, w_i) \tag{1}$$

The priority is handled by the auctioneer, and this new value v'_i is the one used by the clearing algorithm to find an optimal solution. Note however, that the winner bidders will pay the original v_i price.

The function f can be designed in many ways, and it allows introducing different fairness facets in the auction solution. Thus, the function should increase the chances of winning of a high priority agent, while it should decrease the chances of a low priority one. For example, we are currently using the function: $v'_i = f(v_i, w_i) = v_i * w_i$.

Note that this mechanism does not produce any resource waste as it always sells all the available units and reduces the effect of bidder drop problem.

3.2 Customizable Reservation Price Auction (CRPA)

In this mechanism the idea is to have a reservation price for each bidder. We define the reservation price as the minimum price at wich the auctioneer is willing to sell a good or service. That means that the auctioneer does not accept any bid of an agent under its reservation price. The reservation price is initially the same for all the bidders, but it gradually varies as the auctions succeed in the following way. For each agent, if a bid price is higher than the reservation price, then the reservation price is incremented. Otherwise, if the reservation price is higher than the bid's price, then the reservation price is decremented.

A parameter γ is defined indicating the minimum increment and decrement percentage of the reservation price. When a bidder bids with a value higher than its reservation price, then its reservation price is incremented by the half of the difference between the reservation price and the bid's value, except if the difference is lower than γ. In this case, the reservation price is incremented by γ. The algorithm of this procedure is shown in Figure 1.

```
$minimum = reservationPrice_i * \gamma$
$difference = abs(bid_i - reservationPrice_i)$
if $bid_i \geq reservationPrice_i$ then
    $reservationPrice_i = reservationPrice_i + max(difference, minimum)$
else
    $reservationPrice_i = reservationPrice_i - max(difference, minimum)$
end if
```

Fig. 1. Pseudo-code of CRPA reservation price's update

This mechanism is egalitarian since everybody can lose indistinctively of his wealth. In addition, it avoids that bidders with high wealth reduce their price to the minimum possible to win, and it obliges them to increase it to a minimum reservation price. Thus, this mechanism solves the problem of the asymmetric balance of negotiation. However, the use of reservation prices produces resource waste as it does not always allocate all the available resources.

3.3 Customizable Reservation Price Auction with priorities (CRPA+P)

An idea to avoid the resource waste of the previous mechanism is to distribute the remaining resources among the non-winning bidders. Hence what we do is to give the surplus resources to the bidders with higher priority without considering its bid. This fact eliminates the resource waste problem and improves the level of fairness of the solutions.

Therefore, this method is a combination of the CRPA and the PA mechanism, since it is using the individual variable reservation price and the priority mechanism explained above.

4 Experimental setup

In order to test the proposed mechanisms, we have used the experimentation scenario provided in [7] in which recurrent auctions are used to deal with the e-service networking markets. Thus, we use a previously used and tested scenario that corresponds exactly to the multi-unit single-item recurrent auctions.

4.1 Experimentation Scenario

The recurrent auction is formed by 2000 multi-unit auctions. There are 50 units of resources (i.e. time-sensitive e-service units) available for allocation in each auction round. There are 100 customers (bidders). The initial bidding price is randomly selected from the range $[t_i/2, t_i]$, where t_i represents the upper bound on customer i willingness to pay. There are three types of the standard distributions of the upper bound on willingness to pay among the customers, all with a mean of 5: (1) the exponential distribution, (2) the uniform distribution over the range *[0, 10]*, and (3) the gaussian distribution.

Based on the assumption that each bidder will maximize its expected profit, the following bidding behavior have been considered. If a bidder lost in the last auction round, it increases its bidding price by a factor of $\alpha > 1$ to improve its winning probability in the current round. The increase of bidding price is limited by the upper bound on bidder's willingness to pay. If a bidder won in the last auction round, then with equal probability of 0.5, it either decreases the bidding price by a factor β or maintains it unchanged. The decrease attempts to maximize the expected profit. α and β are set in the experiments to 1.2 and 0.8, respectively. The minimum bidding price of a bidder is 0.1.

In order to model the bidder drop problem a Tolerance of Consecutive Losses (TCL) have been defined. The TCL denotes the maximum number of consecutive losses that a customer can tolerate before dropping out of an auction. The TCL value of each customer is uniformly distributed over the range *[2, 10]*.

4.2 Other auction mechanisms

We have compared our mechanism with other previous ones: the traditional auction, the cancelable price auction, the reservation price auction, and the optimal recurrent auction. For such purpose, we have re-implemented them following the information given by the authors on the corresponding papers.

Traditional Auction (TA). In this mechanism the winners are the bidders with the highest bids.

Cancelable Auction (CA). In this type of auction, if the resulting revenue of an auction does not meet the minimum requirements of the auctioneer, the entire auction is canceled. Thus, the cancelation of an auction wastes the entire stock of resources [7].

Reservation Price Auction (RPA). In this mechanism the auctioneer defines a reservation price (the same for all bidders) that indicates the minimum price that the bidders should pay. Only bids higher than the auctioneer's reservation price are considered during the winner selection. In RPA, the reservation price restricts the number of winners and can produce waste of part of the resources.

Optimal Recurring Auction (ORA). Proposed by [7], it is a mechanism based on the demand-supply principle of micro-economics. The mechanism fixes a reservation price b_0 in each auction. This value is the maximum between the $(2R/3)th$ higher bid value in the current auction and the auctioneer's minimum desired benefit of the sold resource. R is the number of resources. Then, all bidders with a bid greater than b_0 become winners. The remaining resources are shared between the loser agents following the VLLF-BDC (Valuable Last Lost first Bidder Drop Control) algorithm [7].

4.3 Parameters

There are several parameters to take into account in the different methods implemented:

- CA. In the experiments the minimum requirements of the auctioneer is set to 250€.
- RPA. The value of reservation price is set to 5€.
- ORA. The auctioneer's minimum desired benefit is set to 5€.
- PA and CRPA+P. We have selected a time window of 10 auction rounds.
- CRPA and CRPA+P:
  - The initial reservation price is set to 5€.
  - The γ factor is set to 0.1.

5 Results

With the aim of measuring the fairness of the system we have used the following two measures:

- **Minimum Won Auctions (MWA)**: It represents the utility of the worst bidder [3]. It is computed as the minimum percentage of won auctions of all of the agents that stay in all of the auctions. A high value of MWA indicates that the mechanism is fair, since the worst bidder is doing quite well.
- **Standard Deviation Won Auctions (DWA)**: the standard deviation of the percentage of won auctions of all of agents. A low DWA indicates that the difference among the agents is low, therefore the fairness of the mechanism is higher.

Figure 2, 3 and 4 show the results obtained. On the right, there is a plot of the average bidding price of winners in each auction mechanism for the wealth distribution. On the right, a table provides some details of the results. The MWA and DWA columns show the values of the fairness metrics. The AWA column shows the Average Won Auctions, the BEN column indicates the total benefit obtained by the auctioneer along the 2000 auction rounds. The NB column shows the number of agents that stay in the auction at the end. Finally, RW shows the number of resources wasted during the recurrent auction.

The results of the plots and tables show that TA is affected in all distributions by the bidder drop problem, causing the decrease of the auctioneer's revenue down to very low values. RPA and CA maintain the auctioneer's revenue at higher values than TA because the balance of the negotiation power is maintained. However they are affected by the resource waste problem (especially RPA), and they are also affected by the bidder drop problem. The number of bidders at the end of the recurrent auction is lower than the bidders in TA.

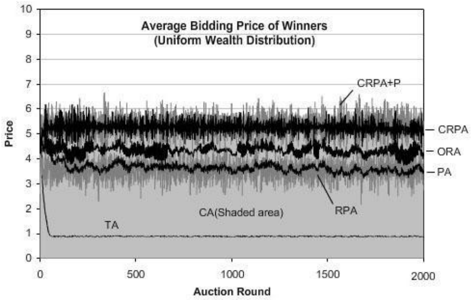
ORA reaches better results than TA, RPA and CA because it is less affected by the bidder drop problem, the resource waste problem and maintains the balance of negotiation power.

The results of PA in uniform wealth distribution are better than RPA but worse than ORA. In the gaussian wealth distribution the results of PA are very similar to ORA and better than RPA, but in the exponential wealth distribution the results obtained show that the auctioneer's revenue falls to very low values because of the balance of negotiation power.

CRPA and CRPA+P show the better results in all the distributions. These mechanisms merge fairness with a strategy to maintain the higher prices that each bidder can pay and consequently obtains very good revenues. The benefits reached by these methods are very similar but CRPA+P maintains a higher number of bidders and does not produce resource waste. Note that CRPA produces resource waste although it is less than CA and RPA. The improved version of CRPA, CRPA+P does not produce any resource waste.

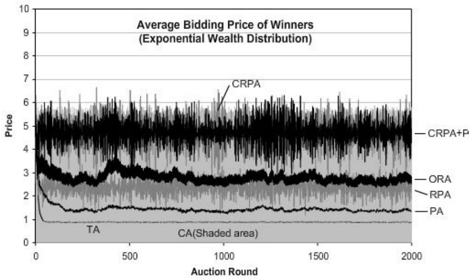
Regarding the fairness measures, the best MWA values are for the CRPA method, followed by the CRPA+P, even that they are quite close. That means, that the variable reserved price helps in guaranteeing the amount of times that an agent wins an auction. On the other hand, the values of DWA are similar for the ORA, PA and CRPA and they are fairer than CA, RPA and TA. The fairest method is CRPA+P. That is, using our CRPA+P mechanism all the agents are winning in a more egalitarian way, while maintaining the benefits of the auctioneer.

Finally, the highest AWA value obtained is when using our CRPA+P method. Since the DWA is also the lowest, we are increasing the number of times any agent wins an auction.



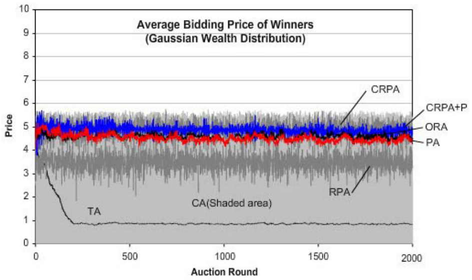
	MWA	DWA	AWA	BEN	NB	RW
TA	60.8	38.5	50.0	1862.3	66	0
CA	35.4	28.8	36.0	7608.1	57	29850
RPA	49.6	30.9	32.6	7100.3	53	34866
ORA	47.7	20.1	50.0	8697.2	87	0
PA	22.4	21.4	50.3	7311.3	85	0
CRPA	53.5	17.7	47.8	10659.7	88	4435
CRPA+P	52.6	6.3	52.2	10526.7	91	0

Fig. 2. Results for the uniform wealth distribution. *Left*: Average bidding price of winners. *Right*: performance measures.



	MWA	DWA	AWA	BEN	NB	RW
TA	61.0	42.6	50.0	1827.3	61	0
CA	58.1	29.0	33.4	6479.3	50	40100
RPA	49.3	29.5	21.9	4780.5	36	56166
ORA	49.7	17.7	50.0	5617.1	90	0
PA	51.8	26.3	50.0	2933.0	79	0
CRPA	54.0	21.4	43.9	9421.1	81	12080
CRPA+P	47.1	2.9	51.6	9455.3	95	0

Fig. 3. Results for the exponential wealth distribution. *Left*: Average bidding price of winners. *Right*: performance measures.



	MWA	DWA	AWA	BEN	NB	RW
TA	60.8	28.3	50.0	2026.2	77	0
CA	31.2	27.0	35.8	7032.5	57	30400
RPA	49.8	30.0	32.3	6965.0	54	35391
ORA	47.8	16.9	51.8	9192.6	87	0
PA	25.9	14.0	53.0	9040.3	87	0
CRPA	53.3	18.4	47.2	9713.5	87	5505
CRPA+P	52.7	1.8	53.5	9726.1	91	0

Fig. 4. Results for the exponential wealth distribution. *Left*: Average bidding price of winners. *Right*: performance measures.

6 Related work

Regarding auctions, it is important to distinguish between recurring, continuous and iterative auctions. Recurring auctions, as the one described in this paper, are related to auctions that are repeated over time, getting a solution in each execution. Continuous auctions [5] are auctions that accept bids anytime, and clear the market as soon as offers arrive. Finally, iterative auctions are the ones that are repeated, but in each round, the solution is considered an approximation. The auction ends whenever the agents repeat the bids or each agent wins some bid [11].

There are few previous works related to egalitarian behavior in auctions, since most researchers have been focussed on an utilitarian point of view. More recently, due to the problems caused by recurrent auctions, this social welfare criteria has started to be a matter of study. For example, in [7] a mechanism based on reservation prices is proposed. In fact, our variable reservation price mechanism is based on it. Another interesting work is [1], where the authors propose the use of leximin preorder in order to establish a trade-off between utility and egalitarian approaches. In this case, however, the scenario considered is a combinatorial auction instead of a recurrent one.

Finally, regarding our priority mechanism, it has been tested in a wastewater treatment plant domain in [10, 9].

7 Conclusions and future work

Auctions are becoming a popular method for dealing with resource allocation in multi-agent systems. When resources are either renewable or perishable, recurrent auctions are required. These auctions are known to have several problems: the resource waste problem, the bidder drop problem and the asymmetric balance of negotiating power. All these problems have been discussed in this paper, and three new recurrent auction mechanisms have been proposed to cope with them: the use of priorities (priority auction), the use of a variable reservation prices (customizable reservation price auction), and a combination of both (customizable reservation price auction with priorities). We have compared the new mechanisms with well-known auction mechanisms and the results show that our customizable reservation price auction with priorities mechanism achieves the highest benefits. This is due to the fact that the mechanism avoids the resource waste problem, maintains the balance of negotiation power and minimizes the effects of bidder drop problem thanks to the fair solutions. The fairness of the mechanism incentives the participation of bidders and consequently improves the auctioneer benefits.

Our future work includes two main directions, one related to the experimentation scenario, and the second one to the auction mechanism. Regarding the experimentation scenario, we are first planning to allow bidders to have a variable demand. In this sense they could bid for different amount of resources (currently only one unit is allowed) or in some auction rounds they could not bid for any resource. Secondly, we want to consider the resource provider (auctioneer) to not have always the same amount of resources, consequently the experimentation scenario could be extended to allow a variable resource supply. This fact can affect the auction mechanism in time of resource scarcity. Regarding the auction mechanism, we are considering to extend it in order to be combinatorial. That means that several items can be considered in a single auction.

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