Limitations of the Vickrey Auction in Computational Multiagent Systems

Tuomas Sandholm *
sandholm@cs.wustl.edu
Washington University
Department of Computer Science
One Brookings Drive, Campus Box 1045
St. Louis, MO 63130-4899

Abstract

Auctions provide an efficient distributed mechanism for solving problems such as task and resource allocation in multiagent systems. In the Vickrey auction—which has been widely advocated for automated auctions [22; 1; 3; 5; 24; 2; 8; 9; 20; 13]—the best bid wins the auction, but at the second best price. In certain settings this promotes truthful bidding and avoids counterspeculation. This paper analyses the circumstances when this protocol is appropriate, and explicates the desirable properties and lack thereof in varied settings. The first part of the paper discusses known deficiencies of the Vickrey auction: bidder collusion, a lying auctioneer, promotion of lying in non-private-value auctions, lower revenue than alternative protocols, and the necessity to reveal sensitive information. The second part of the paper presents our results regarding new limitations of the protocol, which arise especially among computational agents. These include inefficient allocation and lying in sequential auctions of interrelated items, untruthful bidding when a risk averse agent has local uncertainty, and the need for counterspeculation to make deliberation control (or information gathering) decisions when an agent has local uncertainty.

*This material is based upon work supported by the National Science Foundation under Grant No. IRI-9523419. Additional support came from a University of Massachusetts at Amherst Graduate School Fellowship. Also supported by the Technical Research Centre of Finland, Finnish Culture Foundation, Finnish Science Academy, Leo and Regina Wainstein Foundation, Jenny and Antti Wihuri Foundation, Honkanen Foundation, Ella and George Ehrnrooth Foundation, Finnish Information Technology Research Foundation, Transportation Economic Society, and Thanks to Scandinavia Foundation.

1 Introduction

Auctions provide efficient, distributed and autonomy preserving ways of solving task and resource allocation problems in computational multiagent systems [16; 21; 5; 24; 2; 8]. Auctions can be used among cooperative agents, but they also work in open systems consisting of self-interested agents. They can be analyzed *normatively*: what strategies are self-interested agents best off using (and therefore will use), and will desirable social outcomes—e.g. efficient allocation—still follow. The goal is to design the protocols (mechanisms) of the interaction so that desirable social outcomes follow even though each agent acts based on self-interest.

Auction theory analyzes protocols and agents' strategies in auctions. An auction consists of an auctioneer and potential bidders [1]. Auctions are usually discussed regarding situations where the auctioneer wants to sell an item and get the highest possible payment for it while each bidder wants to acquire the item at the lowest possible price. However, settings where the auctioneer wants to subcontract out a task at the lowest possible price and each bidder wants to handle the task at the highest possible payment, are totally analogous.

There are three qualitatively different auction settings depending on how an agent's value of the item is formed. In *private value* auctions, the value of the good depends only on the agent's own preferences. An example is auctioning off a cake that the winning bidder will eat. The key is that the winning bidder will not resell the item in which case the value would depend on other agents' valuations. On the other hand, in *common value* auctions, an agent's value of an item depends entirely on other agents' values of it, which are identical to the agent's by symmetry of this criterion. For example, auctioning treasury bills fulfills this criterion. Nobody inherently prefers having the bills, and the value of the bill comes entirely from reselling possibilities. In *correlated value* auctions, an

[1] There are also auctions with multiple bid takers, i.e. auctioneers.

agent's value depends partly on its own preferences and partly on others' values. For example, an auction in a task contracting setting fulfills this criterion. An agent may handle a task itself in which case the agent's local concerns define the cost of handling the task. On the other hand, the agent can recontract out the task in which case the cost depends solely on other agents' valuations. Next, I discuss four different auction protocols [12].

In the *English (first-price open-cry) auction*, each bidder is free to raise his bid. When no bidder is willing to raise anymore, the auction ends, and the highest bidder wins the item at the price of his bid. An agent's strategy is a series of bids as a function of his private value, his prior estimates of other bidder's valuations, and the past bids of others. In private value English auctions, an agent's dominant strategy is to always bid a small amount more than the current highest bid, and stop when his private value price is reached. In correlated value auctions the rules are often varied to make the auctioneer increase the price at a constant rate or at a rate he thinks appropriate. Secondly, sometimes *open-exit* is used where a bidder has to openly declare exiting without a re-entering possibility. This provides the other bidders more information regarding the agent's valuation.

In the *first-price sealed-bid auction*, each bidder submits one bid without knowing the others' bids. The highest bidder wins the item and pays the amount of his bid. An agent's strategy is his bid as a function of his private value and prior beliefs of others' valuations. In general there is no dominant strategy for acting in this auction. With common knowledge assumptions regarding the probability distributions of the agents' values, it is possible to determine Nash equilibrium strategies for the agents [12].

In the *Dutch (descending) auction*, the seller continuously lowers the price until one of the bidders takes the item at the current price. The Dutch auction is strategically equivalent to the first-price sealed-bid auction, because in both games, an agent's bid matters only if it is the highest, and no relevant information is revealed during the auction process.

In the *Vickrey (second-price sealed-bid) auction*, each bidder submits one bid without knowing the others' bids. The highest bidder wins, but at the price of the second highest bid [23; 11; 12; 7; 4]. An agent's strategy is his bid as a function of his private value and prior beliefs of others' valuations. The dominant strategy in private value Vickrey auctions is to bid one's true valuation. If an agent bids more than that, and the increment made the difference between winning or not, he will end up with a loss if he wins. If he bids less, there is a smaller chance of winning, but the winning price is unaffected [2]. The dominant strategy result of Vickrey auctions means that an agent is best off bidding truthfully no matter what the other bidders are like: what are their capabilities, operating environments, bidding plans, etc. This has two desirable sides. First, the agents reveal their preferences truthfully which allows globally efficient decisions to be made. Second, the agents need not waste effort in counterspeculating other agents, because they do not matter in making the bidding decision.

Vickrey auctions have been widely advocated and adopted for use in computational multiagent systems [22; 1; 3; 5; 24; 2; 8; 9; 20; 13]. For example, versions of the Vickrey auction have been used to allocate computation resources in operating systems [24; 2], to allocate bandwidth in computer networks [22; 8; 9; 20], and to computationally control building environments [5]. On the other hand, Vickrey auctions have not been widely adopted in auctions among humans [14; 15] even though the protocol was laid out 25 years ago [23].

There are severe limitations to the applicability of the Vickrey auction protocol. This paper explores these limitations. It is important to understand these limitations in order not to ascribe desirable characteristics to a protocol when the protocol really does not guarantee them. On the other hand, the Vickrey auction protocol may well be a good choice in situations that do not exceed the applicability limits.

The first part of the paper details the known problems regarding the Vickrey auction. These problems have been discovered by auction theorists and practitioners, and they have led to the lack of deployment of Vickrey auctions among humans. The problems include bidder collusion (Section 2), an untruthful auctioneer (Section 3), lying in non-private-value auctions (Section 4), lower revenue than alternative protocols (Section 5), and the necessity to reveal sensitive information (Section 6). The wide application plans of Vickrey auctions in computational multiagent systems suggest that these limitations may have been forgotten. The first part of the paper serves as a reminder.

The second part of the paper presents our results regarding new limitations of the Vickrey auction protocol. The settings that suffer from these new problems arise especially among computational agents. The newly discovered problems include inefficient allocation and lying in auctions of interrelated items (Section 7), untruthful bidding when an agent has local uncertainty (Section 8), and the need for counterspeculation when an agent has local uncertainty (Section 9).

[2] In private value auctions, the Vickrey auction is strategically equivalent to the English auction. They will produce the same allocation at the same prices. On the other hand, in correlated value auctions, the bids of other agents in the English auction provide information to the agent about its own valuation. Therefore English and Vickrey auctions are not strategically equivalent in general, and may lead to different results.

2 Vulnerability to bidder collusion

One problem with all four of the auction mechanisms (English auction, Dutch auction, first-price sealed-bid auction, and Vickrey auction) is that they are not collusion proof. The bidders could coordinate their bid prices so that the bids stay artificially low. In this manner, the bidders get the item at a lower price than they would without colluding.

The English auction and the Vickrey auction actually self-enforce some of the most likely collusion agreements. Therefore, from the perspective of deterring collusion, the first-price sealed-bid and the Dutch auctions are preferable. The following example from [12] shows this.

Let bidder Smith have value 20, and every other bidder have value 18 for the auctioned item. Say that the bidders collude by deciding that Smith will bid 6, and everyone else will bid 5. In an English auction this is self-enforcing, because if one of the other agents exceeds 5, Smith will observe this, and be willing to go all the way up to 20, and the cheater will not gain anything from breaking the coalition agreement. In the Vickrey auction, the collusion agreement can just as well be that Smith bids 20, because Smith will get the item for 5 anyway. Bidding 20 removes the incentive from any bidder to break the coalition agreement by bidding between 5 and 18, because no such bid would win the auction. On the other hand, in a first-price sealed-bid auction, if Smith bids anything below 18, the other agents have an incentive to bid higher than Smith's bid and to win the contract. The same holds for the Dutch auction.

However, for collusion to occur under the Vickrey auction, the first-price sealed-bid auction, or the Dutch auction, the bidders need to identify each other before the submission of bids—otherwise a non-member of the coalition could win the auction. On the other hand, in the English auction this is not necessary, because the bidders identify themselves by shouting bids. An auctioneer can organize a computerized English auction where the bidding process does not reveal the identities of the bidders.

3 Vulnerability to a lying auctioneer

The insincerity of the auctioneer may be a problem in the Vickrey auction. The auctioneer may overstate the second highest bid to the highest bidder unless that bidder can verify it. An overstated second offer would give the bidder a higher bill than it would receive if the contractor were truthful. In other words, the theory classically assumes a truthful auctioneer. Alternatively, cryptographic electronic signatures could perhaps be used by the bidders so that the auctioneer could actually present the second best bid to the winning bidder—and would not be able to alter it.

The other three auction protocols (English, Dutch, and first-price sealed-bid) do not suffer from lying by the auctioneer because the highest bidder gets the item at the price that it stated in the bid.

Cheating by the auctioneer has been suggested to be one of the main reasons why the Vickrey auction protocol has not been widely adopted in auctions among humans [15]. In another paper, two formal models of cheating by the auctioneer are discussed [14]. The first model is game theoretic. It analyses the situation where the auctioneer can choose to use a first-price sealed-bid protocol or a Vickrey protocol. The bidders' equilibrium behavior creates positive incentives for all auctioneers, except the type most prone to cheat, to choose standard first-price sealed-bid auctions. The second model assumes simple (not rational) bidders. They bid honestly as long as the auctioneer has not been caught cheating, but after catching a cheating auctioneer, the bidders will bid as if the auctioneer always cheats. The result is that a seller with probabilistic opportunities to cheat, and finite abilities to resist cheating, will cheat and be caught in finite time and thereafter have no reason to conduct Vickrey auctions.

4 Lying in non-private-value auctions

Most auctions are not pure private value auctions: an agent's valuation of a good depends at least in part on the other agents' valuations of that good. For example in contracting settings, a bidder's evaluation of a task is affected by the prices at which the agent can subcontract the task or parts of it out to other agents. This type of recontracting is commonly allowed in automated versions of the contract net protocol also [16; 21].

Common value (and correlated value) auctions suffer from the *winner's curse*. If an agent bids its valuation and wins the auction, it will know that its valuation was too high because the other agents bid less. Therefore winning the auction amounts to a monetary loss. Knowing this in advance, agents should bid less than their valuations [11; 12]. This is the best strategy in this type of Vickrey auctions also. So, even though Vickrey auctions promote truthful bidding in private-value auctions where an agent's valuation is totally determined locally, it fails to induce truthful bidding in most auctions.

5 Lower revenue than with the English auction

When considering one auction in isolation, each one of the four auction protocols (English, Dutch, first-price sealed-bid, and Vickrey) allocates the auctioned item Pareto efficiently to the bidder who values it the most. One would imagine that the first-price auctions give higher expected revenue to the auctioneer because in second-price auctions the auctioneer only gets the second price. This is not the case however, because in first-price auctions the bidders are motivated to lie by biasing their bids downward. The *revenue-equivalence theorem* [23; 11; 12] states that all four auction protocols produce the same expected revenue to the auctioneer in private value auctions where the values are independently distributed. Although all four are Pareto efficient in the allocation, the ones with dominant strategies (Vickrey auction and English auction) are more efficient in the sense that no effort needs to be wasted in counterspeculating the other bidders.

However, most auctions are not pure private value auctions as discussed earlier. In correlated value auctions with at least three bidders, the open-exit English auction leads to higher revenue than the Vickrey auction. The reason is that other bidders willing to go high up in price causes a bidder to up its own valuation of the auctioned item. In this type of auctions, both English and Vickrey auction protocols produce greater revenue to the auctioneer than the first-price sealed-bid auction—or its equivalent, the Dutch auction. Put together, the English auction seems to be the right choice by the auctioneer because it creates the greatest revenue, allocates the item optimally, avoids bidders wastefully counterspeculating each other, and has no question of a lying auctioneer.

6 Undesirable private information revelation

Because the Vickrey auction has truthful bidding as the dominant strategy in private value auctions, agents often bid truthfully. This leads to the bidders revealing their true valuations. Sometimes this information is sensitive, and the bidders would prefer not to reveal it. For example, after winning a contract with a low bid, a company's subcontractors figure out that the company's production cost is low, and therefore the company is making larger profits than the subcontractors thought. It has been observed that when such auction results are revealed, the subcontractors will want to renegotiate their deals to get higher payoff [15]. This has been suggested—along with the problem of a lying auctioneer—as one of the main reasons why the Vickrey auction protocol has not been widely adopted in auctions among humans [15].

First-price auction protocols do not expose a bidder's valuation as clearly because the bid is subject to strategic lying. Therefore, these auction types may be more desirable than the Vickrey auction when valuations are sensitive.

The next sections present our results regarding previously unvoiced limitations of the Vickrey auction.

7 Inefficient allocation and lying in interrelated auctions

In addition to single-item auctions, Vickrey auctions have been widely studied in the allocation of multiple items of a homogeneous good [11]. However, the case of auctioning heterogeneous interrelated goods has received little attention. On the other hand this is the setting of many real world problems where computational agents are used [18; 17; 19; 16; 13].

This section discusses cases where heterogeneous items are auctioned one at a time, and the agents' valuations of these items are not additive. This occurs for example in task allocation in transportation problems. Figure 1 presents a simple example of such a problem with just two delivery tasks: t_1 and t_2. The former task is auctioned before the latter. The auctioneer wants to get the tasks handled while paying agents 1 and 2 as little as possible for handling them. The initial locations of the two agents are presented in the figure. To handle a task, an agent needs to move to the beginning of the arrow, and take a parcel from there to the end of the arrow. An agent's movement incurs the same cost irrespective of whether it is carrying a parcel. The agents need not return to their initial locations. The costs for handling tasks (subscripted by the name of the agent) can be measured from the figure: $c_1(\{t_1\}) = 2$, $c_1(\{t_2\}) = 1$, $c_1(\{t_1, t_2\}) = 2$, $c_2(\{t_1\}) = 1.5$, $c_2(\{t_2\}) = 1.5$, and $c_2(\{t_1, t_2\}) = 2.5$. These costs are common knowledge to the agents. Clearly the globally optimal allocation is the one where agent 1 handles both tasks. This allocation is not reached if agents treat the auctions independently and bid truthfully:

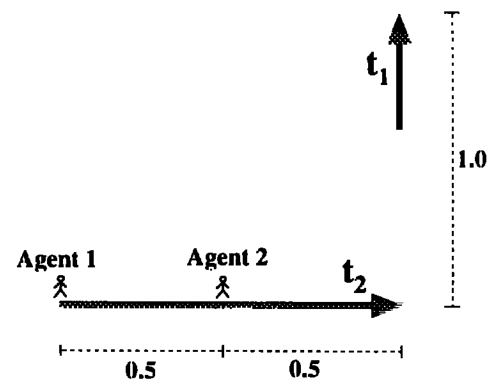

Figure 1: *Small example problem with two agents and two delivery tasks.*

Theorem 7.1 ***Suboptimal allocation in interrelated auctions.*** *If agents with deterministic valuations treat Vickrey auctions of interdependent goods without lookahead regarding later auctions, and bid truthfully, the resulting allocation may be suboptimal.*

Proof. Example of Figure 1. In the first auction, task t_1 is allocated. Agent 1 bids $c_1(\{t_1\}) = 2$, and agent 2 bids $c_2(\{t_1\}) = 1.5$. The task is allocated to agent 2. In the second auction, task t_2 is allocated. Agent 1 bids $c_1(\{t_2\}) = 1$, and agent 2 bids

$c_2(\{t_2\}) = 1.5$, so t_2 is allocated to agent 1. The resulting allocation of the two tasks is suboptimal.

If agent 2 takes the ownership of t_1 into account when bidding for t_2, then it will bid $c_2(\{t_1, t_2\}) - c_2(\{t_1\}) = 2.5 - 1.5 = 1$. In this case t_2 may be allocated to either agent. In both cases the resulting allocation of the two tasks is still suboptimal. □

Alternatively, the agents can incorporate full lookahead into their auction strategies. This way the optimal allocation is reached, but agents do not bid their true costs:

Theorem 7.2 ***Untruthful bidding in interrelated auctions.*** *If agents with deterministic valuations treat Vickrey auctions of interdependent goods with full lookahead regarding later auctions, their dominant strategy bids can differ from the truthful ones of the corresponding isolated auctions.*

Proof. Example of Figure 1. In the last auction, an agent is best off bidding its own costs that takes into account the tasks that the agent already has. Let us look at the auction of t_2. If agent 1 has t_1, it will bid $c_1(\{t_1, t_2\}) - c_1(\{t_1\}) = 2 - 2 = 0$, and $c_1(\{t_2\}) = 1$ otherwise. If agent 2 has t_1, it will bid $c_2(\{t_1, t_2\}) - c_2(\{t_1\}) = 2.5 - 1.5 = 1$, and $c_2(\{t_2\}) = 1.5$ otherwise. So, if agent 1 has t_1, it will win t_2 at the price 1.5, and get a payoff of $1.5 - 0 = 1.5$ in the second auction, while agent 2 gets zero. On the other hand, if agent 2 has t_1, the bids for t_2 are equal, and both agents get a zero payoff in the second auction—irrespective of who t_2 gets allocated to.

Therefore it is known that getting t_1 in the first auction is worth an extra 1.5 to agent 1 while nothing extra to agent 2. So, in the auction for t_1, agent 1's dominant strategy is to bid $c_1(\{t_1\}) - 1.5 = 2 - 1.5 = 0.5$. This is lower than agent 2's bid $c_2(\{t_1\}) - 0 = 1.5 - 0 = 1.5$, so agent one gets t_1. In the second auction agent 1 gets t_2 as discussed above. So the globally optimal allocation is reached.

However, agent 1 bids 0.5 for t_1 instead of 2, which would be the truthful bid if the auctions were treated independently without lookahead. □

Put together, lookahead is a key feature in auctions of multiple interrelated items. Up to date it has not been adequately addressed in computational multiagent systems that use Vickrey auctions. In auctions by humans, this issue is sometimes addressed by allowing a bidder to pool all of the interrelated items under one *entirety bid* [11]. Another method for enhancing the efficiency of interrelated auctions is to allow agents to backtrack from commitments by paying penalties. This allows a winning agent to beneficially decommit from an auctioned item in case that agent does not get synergic items from other related auctions [10; 19].

While avoidance of counterspeculation was one of the original reasons suggested for adopting the Vickrey auction, lookahead requires counterspeculation in the sense of trying to guess which items are going to be auctioned in the future. Other speculative issues in sequential Vickrey auctions have been discussed for example in [6].

8 Untruthful bidding with local uncertainty

Agents often have uncertainty about the worth of the auction item to themselves. This valuation may be inherently uncertain. On the other hand, computational agents may have uncertainty regarding local evaluation because computing the valuation may be complex, and the computation may not have finished by the time of the auction. Such computational complexities arise for example in task allocation auctions where evaluating a task set requires solving NP-complete problems [18; 17; 19; 16; 13].

Risk neutral agents—i.e. agents with linear utility functions—are best off bidding the expected value of their valuation in a single-shot private value Vickrey auction. This is a dominant strategy. However, many agents are risk averse, i.e. their utility is a concave function of payoff. For example, many people would prefer $100,000,000 for certain over a fifty-fifty chance of receiving $200,000,001. Computational agents take on the preferences of the real world parties that they represent. Therefore many computational agents will be risk averse. The following theorem states the result that risk averse agents are not best off bidding truthfully when the Vickrey auction protocol is used. Thus it is nonobvious that the Vickrey auction protocol can really be used in computational systems to avoid lying.

Theorem 8.1 ***Untruthful bidding.*** *It is not the case that in a single-shot private value Vickrey auction with uncertainty about an agent's own valuation, it is a risk averse agent's best (dominant or equilibrium) strategy to bid its expected value.*

Proof. Counterexample. We will analyze an auction where the auctioneer wants to get a high price for a good, but task allocation auctions where the auctioneer wants to allocate the task at a low price are analogous. Let the agent's utility function be $U(x) = \begin{cases} 2x & \text{if } x \leq 0 \\ x & \text{if } x > 0. \end{cases}$ The concavity of this function represents risk aversion of the agent. Let the agent's own valuation v be uniformly distributed between 0 and 1. We now show that the agent can increase its expected utility by bidding $E[v] - \epsilon$ instead of $E[v]$. We analyze the situation based on what the highest bid b coming from other agents might be.

Case 1: $b \leq E[v] - \epsilon$. In this case, the agent wins the auction at price b when bidding $E[v]$ or $E[v] - \epsilon$. Therefore the expected utility is unaffected by bidding $E[v] - \epsilon$ instead of $E[v]$.

Case 2: $b \geq E[v]$. In this case, the agent loses the auction when bidding $E[v]$ or $E[v] - \epsilon$. Therefore the expected utility $U(0) = 0$ is unaffected by bidding $E[v] - \epsilon$ instead of $E[v]$.

Case 3: $E[v] - \epsilon < b < E[v]$. In this case, the agent loses the contract when bidding $E[v] - \epsilon$, but wins it when bidding $E[v]$. Therefore, the utility from bidding $E[v] - \epsilon$ is $U(0) = 0$. The expected utility from bidding $E[v]$ is

$$\begin{aligned}\int_{-\infty}^{\infty} U(v-b)dv &= \int_0^b 2(v-b)dv + \int_b^1 v - bdv \\ &= -\frac{1}{2}b^2 - b + \frac{1}{2}\end{aligned}$$

which is less than zero when $b > \frac{-2+\sqrt{8}}{2} \approx 0.41$ (i.e. in the range of case 3). So, bidding $E[v]$ has *smaller* expected utility than bidding $E[v] - \epsilon$. □

9 Wasteful counterspeculation

One of the main original motivations for using the Vickrey auction was that an agent has a dominant strategy (of telling the truth), i.e. an agent's best action does not depend on other agents. Therefore the bidders will not waste effort in counterspeculating each other. This would lead to global savings.

This section presents a new result which states that there are cases where the Vickrey auction fails to have this desirable property. Let us look at a situation where an agent has uncertainty regarding its own valuation of the auction item, but can pay to remove this uncertainty. This situation often occurs among computational agents, where the value of a good (or task contract [18; 17; 19; 16; 13]) can only be determined via carrying out a costly computation—e.g. a solution of a combinatorial problem. Alternatively the payment can be viewed as the cost of solving a prediction problem, or as the cost of performing an information gathering action, or as the cost paid to an expert oracle. The following theorem states that in such a setting, the Vickrey auction protocol does not avoid counterspeculation.

Theorem 9.1 ***Incentive to counterspeculate.*** *In a single-shot private value Vickrey auction with uncertainty about an agent's own valuation, a risk neutral agent's best (deliberation or information gathering) action can depend on the other agents.*

Proof. Proof by example. We will analyze an auction where the auctioneer wants to get a high price for a good, but task allocation auctions where the auctioneer wants to allocate the task at a low price are analogous. Let there be one auctioneer, and two bidder agents: 1 and 2. Let agent 1's own valuation v_1 for the auctioned item be uniformly distributed between 0 and 1, i.e. agent 1 does not know its own valuation exactly. On the other hand, let agent 2's exact valuation v_2 be common knowledge. Let us restrict ourselves to the situation where $0 \leq v_2 < \frac{1}{2}$, which implies $E[v_1] > v_2$.

Let agent 1 have the choice of finding out its exact valuation v_1 before the auction by paying a cost c. Now, should agent 1 take this informative but costly action?

No matter what agent 1 chooses here, agent 2 will bid v_2 because bidding ones valuation is a dominant strategy in a single-shot private value Vickrey auction.

If agent 1 chooses to not pay c, agent 1 should bid $E[v_1] = \frac{1}{2}$, because bidding ones expected valuation is a risk neutral agent's dominant strategy in a single-shot private value Vickrey auction. Now agent 1 gets the item at price v_2. If agent 1's valuation v_1 turns out to be less than v_2, agent 1 will suffer a loss. Agent 1's expected payoff is

$$E[\Pi_{noinfo}] = \int_0^1 v_1 - v_2 dv_1 = \frac{1}{2} - v_2$$

On the other hand, if agent 1 chooses to pay c for the exact information, it should bid v_1 because bidding ones valuation is a dominant strategy in a single-shot private value Vickrey auction. Agent 1 gets the item if *and only if* $v_1 \geq v_2$. Note that now the agent has no chance of suffering a loss, but on the other hand it has invested c in the information. Agent 1's expected payoff is

$$\begin{aligned}E[\Pi_{info}] &= \int_0^{v_2} -c dv_1 + \int_{v_2}^1 v_1 - v_2 - c dv_1 \\ &= \frac{1}{2}v_2^2 - v_2 + \frac{1}{2} - c\end{aligned}$$

Agent 1 should choose to buy the information iff

$$\begin{aligned}& E[\Pi_{info}] \geq E[\Pi_{noinfo}] \\ \Leftrightarrow\ & \frac{1}{2}v_2^2 - v_2 + \frac{1}{2} - c \geq \frac{1}{2} - v_2 \\ \Leftrightarrow\ & \frac{1}{2}v_2^2 \geq c \\ \Leftrightarrow\ & v_2 \geq \sqrt{2c} \qquad \text{(because } v_2 \geq 0\text{)}\end{aligned}$$

So, agent 1's best choice of action depends on agent 2's valuation v_2. Therefore, agent 1 benefits from counterspeculating agent 2. □

10 Conclusions

Vickrey auctions have been widely suggested and adopted for use in computational multiagent systems [22; 1; 3; 5; 24; 2; 8; 9; 20; 13]. This auction protocol has certain desirable properties—such as truth-promotion and counterspeculation avoidance—in limited settings. It is important to clearly understand these limitations in order not to use the protocol when inappropriate, and in order not to trust the protocol to have certain desirable properties when it really does not have them in the particular setting.

The first part of the paper detailed known problems regarding the Vickrey auction. These include bidder collusion, a lying auctioneer, promotion of lying in non-private-value auctions, lower revenue than alternative protocols, and the necessity to reveal sensitive information.

The second part of the paper presented our results regarding new limitations of the protocol. The settings that suffer from these new problems arise especially among computational agents. The problems include inefficient allocation and lying in sequential auctions of interrelated items, untruthful bidding when a risk averse agent has local uncertainty, and the need for counterspeculation to make deliberation control (or information gathering) decisions when an agent has local uncertainty.

References

[1] Agorics, Inc. Going, going, gone! A survey of auction types. *http://www.agorics.com /agorics /auctions /bibliography.html*, 1996.

[2] K. E. Drexler and M. S. Miller. Incentive engineering for computational resource management. In B. A. Huberman, editor, *The Ecology of Computation*. North-Holland, 1988.

[3] J. Edelman. Web page mention of the use of Vickrey auction in AgentTCL. *http: //www.cs.dartmouth.edu/ ~jze/ resume.html*, 1996.

[4] D. Fudenberg and J. Tirole. *Game Theory*. MIT Press, 1991.

[5] B. Huberman and S. H. Clearwater. A multi-agent system for controlling building environments. In *Proceedings of the First International Conference on Multi-Agent Systems (ICMAS-95)*, pages 171–176, San Francisco, CA, June 1995.

[6] M. Jackson and J. Peck. Speculation and price fluctuations with private, extrinsic signals. *Journal of Economic Theory*, 55:274–295, 1991.

[7] D. M. Kreps. *A Course in Microeconomic Theory*. Princeton University Press, 1990.

[8] J. K. MacKie-Mason and H. R. Varian. Pricing the internet. In *Proceedings of the Public Access to the Internet Conference*. JFK School of Government, May 1993.

[9] J. K. MacKie-Mason and H. R. Varian. Some FAQs about usage-based pricing. *ftp: //alfred.sims.berkeley.edu /pub /Papers /use-FAQs.html*, 1994.

[10] R. P. McAfee and J. McMillan. Analyzing the airwaves auction. *Journal of Economic Perspectives*, 10(1):159–175, 1996.

[11] P. R. Milgrom. The economics of competitive bidding: a selective survey. In L. Hurwicz, D. Schmeidler, and H. Sonnenschein, editors, *Social goals and social organization: Essays in memory of Elisha Pazner*, chapter 9, pages 261–292. Cambridge University Press, 1985.

[12] E. Rasmusen. *Games and Information*. Basil Blackwell, 1989.

[13] J. S. Rosenschein and G. Zlotkin. *Rules of Encounter*. MIT Press, 1994.

[14] M. H. Rothkopf and R. M. Harstad. Two models of bid-taker cheating in Vickrey auctions. *Journal of Business*, 68(2):257–267, 1995.

[15] M. H. Rothkopf, T. J. Teisberg, and E. P. Kahn. Why are Vickrey auctions rare? *Journal of Political Economy*, 98(1):94–109, 1990.

[16] T. W. Sandholm. An implementation of the contract net protocol based on marginal cost calculations. In *Proc. 11th National Conference on Artificial Intelligence (AAAI-93)*, pages 256–262, July 1993.

[17] T. W. Sandholm and V. R. Lesser. Coalition formation among bounded rational agents. In *Proceedings of the Fourteenth International Joint Conference on Artificial Intelligence*, pages 662–669, Montreal, Canada, Aug. 1995. Extended version appeared as University of Massachusetts at Amherst, Computer Science Department technical report 95-71.

[18] T. W. Sandholm and V. R. Lesser. Issues in automated negotiation and electronic commerce: Extending the contract net framework. In *Proceedings of the First International Conference on Multi-Agent Systems (ICMAS-95)*, pages 328–335, San Francisco, CA, June 1995.

[19] T. W. Sandholm and V. R. Lesser. Advantages of a leveled commitment contracting protocol. In *Proceedings of the National Conference on Artificial Intelligence*, Portland, OR, Aug. 1996. Extended version appeared as University of Massachusetts at Amherst, Computer Science Department technical report 95-72.

[20] Smart Market. Web page mention of the use of Vickrey auction in Smart Market. *http://mortadello.wu-wien.ac.at /~iwork /pricing /smart_market.html*, 1996.

[21] R. G. Smith. The contract net protocol: High-level communication and control in a distributed problem solver. *IEEE Transactions on Computers*, C-29(12):1104–1113, Dec. 1980.

[22] Sun Microsystems. Web page mention of the use of Vickrey auction in Webmart. *http://www.sun.com:80 /960201 /cover /webmart.html*, 1996.

[23] W. Vickrey. Counter speculation, auctions, and competitive sealed tenders. *Journal of Finance*, 16:8–37, 1961.

[24] C. A. Waldspurger, T. Hogg, B. Huberman, J. O. Kephart, and W. S. Stornetta. Spawn: A distributed computational economy. *IEEE Transactions on Software Engineering*, 18(2):103–117, 1992.