Price-oriented, Rationing-free Protocol: Guideline for Designing Strategy/False-name Proof Auction Protocols

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Abstract

We identify a distinctive class of combinatorial auction protocols called a Price-oriented, Rationing-free (PORF) protocol, which can be used as a guideline for developing strategy/false-name proof protocols. A PORF protocol is automatically guaranteed to be *strategy-proof*, i.e., for each agent, declaring its true evaluation values is an optimal strategy regardless of the declarations of other agents. Furthermore, if a PORF protocol satisfies additional conditions, the protocol is also guaranteed to be *false-name-proof*, that is, it eliminates the benefits from using false-name bids, i.e., bids submitted under multiple fictitious names such as multiple e-mail addresses. For Internet auction protocols, being false-name-proof is important since identifying each participant on the Internet is virtually impossible.

The characteristics of a PORF protocol are as follows. For each agent, the price of each bundle of goods is presented. This price is determined based on the declared evaluation values of other agents, while it is independent of its own declaration. Then, each agent can choose the bundle that maximizes its utility independently of the allocations of other agents (i.e., rationing-free). We show that an existing false-name-proof protocol can be represented as a PORF protocol. Furthermore, we develop a new false-name-proof PORF protocol.

Introduction

Internet auctions have become an especially popular part of Electronic Commerce (EC). Among various studies related to Internet auctions, those on combinatorial auctions have lately attracted considerable attention (Fujishima, Leyton-Brown, & Shoham 1999; Klemperer 1999; Sandholm 1999; Lehmann, O'Callaghan, & Shoham 1999). Although conventional auctions sell a single item at a time, combinatorial auctions sell multiple items with interdependent values simultaneously and allow the bidders to bid on any combination of items. In a combinatorial auction, a bidder can express complementary/substitutable preferences over multiple bids. By taking into account complementary/substitutable preferences, we can increase the participants' utilities and the revenue of the seller.

However, the possibility of a new type of cheating called *false-name bids* has been pointed out, i.e., an agent may try to profit from submitting false bids made under fictitious names, e.g., multiple e-mail addresses (Sakurai, Yokoo, & Matsubara 1999; Yokoo, Sakurai, & Matsubara 2001b). Such a dishonest action is very difficult to detect since identifying each participant on the Internet is virtually impossible. Compared with collusion (Klemperer 1999), a false-name bid is easier to execute since it can be done by someone acting alone. We can consider false-name bids a very restricted subset of general collusion.

Yokoo *et al.* have been conducted a series of works on false-name bids. Their results can be summarized as follows.

- The generalized Vickrey auction protocol (GVA) (Varian 1995), which is strategy-proof, individually rational, and Pareto efficient, if there exists no false-name bid, is no longer strategy-proof when false-name bids are possible, i.e., the GVA is not false-name-proof (Sakurai, Yokoo, & Matsubara 1999; Yokoo, Sakurai, & Matsubara 2000).
- There exists no false-name-proof combinatorial auction protocol that simultaneously satisfies Pareto efficiency and individual rationality (Sakurai, Yokoo, & Matsubara 1999; Yokoo, Sakurai, & Matsubara 2000).
- A false-name-proof combinatorial auction protocol called the LDS protocol (Yokoo, Sakurai, & Matsubara 2001b) and a false-name-proof multi-unit auction protocol called the IR protocol (Yokoo, Sakurai, & Matsubara 2001c) were developed.

Developing a strategy/false-name proof protocol has been a difficult task. In this paper, we identify a distinctive class of combinatorial auction protocols called a Price-oriented, Rationing-free (PORF) protocol. The notion of a PORF protocol can be used as a guideline for developing strategy/false-name protocols. More specifically, if a protocol can be represented as a PORF protocol, it is automatically guaranteed to be strategy-proof. Furthermore, if a PORF protocol satisfies additional conditions, it is also guaranteed to be false-name-proof.

In a PORF protocol, for each agent, the price of each bundle of goods is presented. This price is determined based on the declared evaluation values of other agents, while it must be independent of its own declarations. Then, each agent can choose the bundle that maximizes its utility based

on the presented prices, independently of the allocations of other agents.

A PORF protocol is different from a normal fixed-price mechanism, where fixed prices of goods/bundles are determined, and agents choose one or a set of bundles they are willing to buy, then the auctioneer tries to ration the allocation, e.g., to choose winners by using a lottery. In a PORF protocol, the auctioneer does not try to ration the allocation, i.e., if an agent is willing to buy a bundle, the agent is guaranteed to obtain the bundle regardless of the allocations of other agents. In a PORF protocol, the auctioneer must carefully determine the prices so that a feasible allocation, i.e., the allocation where the same good is not allocated to different agents, can be obtained without using a lottery.

We show that various protocols, including the existing false-name-proof protocol called LDS protocol (Yokoo, Sakurai, & Matsubara 2001b) can be represented as a PORF protocol. Furthermore, we develop a new false-name-proof PORF protocol and compare it with the LDS protocol.

Preliminaries

Here, we introduce several basic terms and concepts.

We concentrate on *private value auctions* (Mas-Colell, Whinston, & Green 1995). In private value auctions, each agent knows with certainty its own evaluation values of goods, which are independent of the other agents' evaluation values. We define an agent's utility as the difference between this private value of the allocated bundle, i.e., a set of goods, and its payment. Such a utility is called a *quasi-linear* utility (Mas-Colell, Whinston, & Green 1995). These assumptions are commonly used for making theoretical analyses tractable. Formally, we assume that for each agent i, its type θ_i is drawn from a set Θ. The utility of agent i, who obtains bundle B and an amount of money t_i, is represented as $v(B, \theta_i) + t_i$, where $v(B, \theta_i)$ represents the private value of agent i for bundle B.

In a traditional definition (Mas-Colell, Whinston, & Green 1995), an auction protocol is (dominant-strategy) *incentive compatible* (or *strategy-proof*) if bidding the true private values of goods is a dominant strategy for each agent, i.e., an optimal strategy regardless of the actions of other agents. The revelation principle states that in the design of an auction protocol we can restrict our attention to incentive compatible protocols without loss of generality (Mas-Colell, Whinston, & Green 1995; Yokoo, Sakurai, & Matsubara 2000). In other words, if a certain property (e.g., Pareto efficiency) can be achieved using some auction protocol in a dominant-strategy equilibrium, i.e., a combination of dominant strategies of agents, the property can also be achieved using an incentive compatible auction protocol.

In this paper, we extend the traditional definition of incentive compatibility so that it can address false-name bid manipulations, i.e., we define that an auction protocol is (dominant-strategy) incentive compatible if bidding the true private values of goods by using the true identifier is a dominant strategy for each agent. To distinguish the traditional and extended definition of incentive compatibility, we refer to the traditional definition as strategy-proof and to the extended definition as *false-name-proof*.

We say an auction protocol is *Pareto efficient* when the sum of all participants' utilities (including that of the auctioneer), i.e., the social surplus, is maximized in a dominant-strategy equilibrium. An auction protocol is *individually rational* if no participant suffers any loss in a dominant-strategy equilibrium, i.e., the payment never exceeds the evaluation value of the obtained goods. In a private value auction, individual rationality is indispensable; no agent wants to participate in an auction where it might be charged more money than it is willing to pay. Therefore, in this paper, we restrict our attention to individually rational protocols.

Price-oriented, Rationing-free Protocol

We show the overview of a PORF protocol.

- We assume there is a set of goods $M = \{1, 2, \ldots, m\}$. For each bundle $B \subseteq M$, each agent declares its (not necessarily true) evaluation value.
- For each agent i, the price of each bundle B is calculated. This price can be a *differential price*, i.e., the price of the same bundle can vary for different agents. Also, the price for bundle B does not necessarily have to be *additive*, i.e., the sum of the prices of the goods in the bundle. The price can be super-additive (more than the sum) or sub-additive (less than the sum).
- The price for agent i is totally independent of its own declared evaluation values, while it is based on the declared evaluation values of the agents other than i.
- For agent i, a bundle that maximizes its utility is allocated under the given prices. If there exist multiple bundles that maximize i's utility, the auctioneer can coordinate the allocation and chooses a *feasible* allocation, i.e., the allocation where the same good is not allocated to different agents.
- Unless agent i is totally indifferent among multiple bundles, the auctioneer does not coordinate the allocation, i.e., the bundle allocated to agent i is determined independently of the allocations of the other agents. We call this property *rationing-free*.

Formally, a PORF protocol can be described as follows.

- Each agent i declares its (not necessarily true) type $\tilde{\theta}_i$. We assume an agent can declare multiple types using multiple identifiers.
- We assume a PORF protocol is an *anonymous* protocol, where permuting agents' identifiers does not change the outcome. Let us represent a set of agents other than agent i as X and the set of declared types of X as Θ_X. The price of agent i for bundle B is represented as $P_B(\Theta_X)$, i.e., the function of Θ_X.
- For agent i who declares its type as $\tilde{\theta}_i$, the auctioneer chooses a bundle B^*, where $B^* = \arg\max_B v(B, \tilde{\theta}_i) - P_B(\Theta_X)$. Such a bundle might not be determined uniquely. Let us represent the set of such bundles as SB_i^*.
- The auctioneer determines an allocation, $g = (B_1, B_2, \ldots)$, where $B_i \in SB_i^*$ and for all $i \neq$

$j, B_i \cap B_j = \emptyset$. If the prices are determined appropriately, we can guarantee that the auctioneer is able to choose such a feasible allocation.

If there exists no false-name bid, i.e., an agent can use only one identifier, it is obvious that a PORF protocol is strategy-proof. For agent i, its price for a bundle is determined independently of its declared type. Also, the protocol is rationing-free, i.e., the bundle allocated to agent i is determined so that its utility is maximized, independently of the allocations of other agents. Therefore, over-declaring its evaluation value for bundle B, so that other agents' prices for bundle B would increase and they would give up the idea of buying B, is totally useless.

On the other hand, the auctioneer must set the prices appropriately so that he/she can choose a feasible allocation without rationing. We can see an interesting relationship between a PORF protocol and a traditional protocol, where a feasible allocation is determined first, and then the payment of each agent is determined based on the allocation. In a traditional protocol, it is obvious that the obtained allocation is feasible, but the auctioneer must determine the payment appropriately so that the protocol is strategy-proof. In a PORF protocol, it is obvious that the protocol is strategy-proof, but the auctioneer must determine prices appropriately so that he/she can choose a feasible allocation without rationing.

Examples of PORF Protocols

GVA

In the Vickrey auction protocol for a single-item single-unit auction, the agent who declares the highest evaluation value obtains the good by paying the price that is equal to the second highest evaluation value. This protocol can be described as a PORF protocol as follows. For agent i, the price of the good is the highest evaluation value of agents other than i. It is clear that only one agent is willing to buy the good except for the case of random tie-breaking, where the utility of the winner is 0.

In the generalized Vickrey auction protocol (GVA) (Varian 1995), which can be used for a combinatorial auction, the goods are allocated in a way that maximizes the obtained social surplus, i.e., the sum of all participants' utilities including the auctioneer.

To simplify the protocol description, we introduce the following notation. For a set of agents X and a set of goods S, we define $V^*(X, S)$ as the sum of the evaluation values of X when S is allocated optimally among X. To be precise, for a possible allocation $g = (B_1, B_2, \ldots)$, where $\bigcup_{j \in X} B_j = S$ and for all $x \neq y, B_x \cap B_y = \emptyset$, $V^*(X, S)$ is defined as $\max_g \sum_{j \in X} v(B_j, \tilde{\theta}_j)$, where $\tilde{\theta}_j$ is the declared type of agent j.

The payment of agent i who obtains bundle B is represented as follows, where X is the set of agents other than i:

$$V^*(X, M) - V^*(X, M \setminus B)$$

The first term of this formula represents the optimal social surplus when agent i does not participate in the auction. The second term represents the optimal social surplus except agent i when agent i does participate and obtains bundle B. In the GVA, we can assume each agent is required to pay the decreased amount of social surplus for other agents caused by its participation.

The GVA can be represented as a PORF protocol, where $P_B(\Theta_X)$, i.e., the price of agent i for bundle B, is represented as follows.

$$P_B(\Theta_X) = V^*(X, M) - V^*(X, M \setminus B)$$

It is straightforward to show that the auctioneer can choose a feasible allocation, which also maximizes the social surplus, in this PORF protocol.

Bundle-size Ordered Protocol

We describe a new PORF protocol that is false-name-proof. We call this protocol Bundle-size Ordered (BSO) protocol.

Overview The overview of the BSO protocol is as follows.

- The auctioneer determines the reservation price r_j for each good j, i.e., the auctioneer will not sell good j for less than r_j. For simplicity, we assume that all goods have the same reservation price r. Relaxing this condition is rather straightforward.
- The price of agent i for bundle B is determined as follows. Let us assume k is the size of bundle B, i.e., the number of goods in B. We assume the reservation price of bundle B is $r \times k$.
  Let us assume B' represents the bundle that satisfies the following conditions.
  1. There exists at least one common good between B and B', i.e., $B \cap B' \neq \emptyset$.
  2. For agent $j \neq i$, whose declared type is $\tilde{\theta}_j$, $v(B', \tilde{\theta}_j) \geq r \times k'$, where k' is the size of B', i.e., there exists an agent whose evaluation value for B' is larger than (or equal to) the reservation price of B'.
  3. k' is largest within the bundles that satisfy the above two conditions.
  4. $v(B', \tilde{\theta}_j)$ is largest within the bundles that satisfy the above three conditions.

  Now, the price of agent i for bundle B is defined as follows:

  when $k' > k$: ∞,
  when $k' = k$: $v(B', \tilde{\theta}_j)$,
  when $k' < k$: $r \times k$.

In short, when another agent is willing to pay more than the reservation price for bundle B', which is larger than B and conflicting with B, i.e., B and B' have a common good, then agent i cannot buy B. If the sizes are the same, the agent declaring the highest evaluation value can buy the bundle with the second highest evaluation value. If nobody is willing to pay more than the reservation price for a conflicting bundle with the same or larger size, then the agent can buy the bundle at the reservation price.

Example 1 *Let us assume there are three goods a, b, and c, and the reservation price for each is* 100. *There are two*

agents, agent 1 and agent 2, whose types are θ_1, θ_2, respectively. The evaluation value for a bundle $v(B, \theta_i)$ is determined as follows.

	(a)	(b)	(c)	(a,b)	(b,c)	(a,c)	(a,b,c)
θ_1	0	0	0	210	0	0	210
θ_2	0	110	110	110	110	110	110

These evaluation values mean that agent 1 needs both a and b at the same time, while agent 2 needs either b or c but not both at the same time. In this case, the price of agent 1 for bundle (a, b), i.e., $P_{(a,b)}(\{\theta_2\})$, is 200, i.e., the reservation price, the price of agent 2 for b, i.e., $P_{(b)}(\{\theta_1\})$, is ∞ due to agent 1's evaluation value for (a, b), and the price of agent 2 for c, i.e., $P_{(c)}(\{\theta_1\})$, is 100, i.e., the reservation price. As a result, agent 1 obtains bundle (a, b) for 200 and agent 2 obtains c for 100.

Example 2 *The number of goods and reservation prices are identical to Example 1. There exist three agents whose types are as follows.*

	(a)	(b)	(c)	(a,b)	(b,c)	(a,c)	(a,b,c)
θ_1	0	0	0	210	0	0	210
θ_2	0	0	0	0	205	0	205
θ_3	0	0	150	0	150	150	150

Agent 1 needs both a and b at the same time and agent 2 needs both b and c at the same time, while agent 3 needs only c. In this case, the price of agent 1 for bundle (a, b) is 205 due to agent 2's evaluation value for (b, c), the price of agent 2 for bundle (b, c) is 210 due to agent 1's evaluation value for (a, b), and the price of agent 3 for c is ∞ due to agent 2's evaluation value for (b, c). As a result, agent 1 obtains bundle (a, b) for 205, while c cannot be allocated.

Allocation Feasibility Here, we show that the auctioneer can always choose a feasible allocation in the BSO protocol. More specifically, we show that for any bundle that contains good a, there exists at most one agent who is willing to buy such a bundle, except when multiple agents are willing to buy the bundle but the utilities of these agents are 0. If the utility of an agent is 0, the agent is indifferent between obtaining and not obtaining the bundle. Therefore, the auctioneer can coordinate and choose a feasible allocation.

First, let us choose the bundle B_{max} that satisfies the following conditions.

1. B_{max} contains good a.
2. For agent i, whose type is θ_i, $v(B_{max}, \theta_i) \geq r \times k_{max}$, where k_{max} is the size of B_{max}. We assume each agent is declaring its true type since the protocol is strategy-proof.
3. k_{max} is largest within the bundles that satisfy the above two conditions.
4. $v(B_{max}, \theta_i)$ is largest within the bundles that satisfy the above three conditions.

For agent j where $j \neq i$, the price of agent j for bundle B that contains a is determined as follows. Let us represent the size of B as k. If $v(B, \theta_j) \geq r \times k$, by this way of choosing B_{max}, $k_{max} \geq k$ holds.

level 1	[{(a,b,c,d)}]
level 2	[{(a,b,c)}, {(b,c,d)}, {(a,c,d)}]
level 3	[{(a,b),(c,d)}, {(a,c),(b,d)}, {(a,d),(b,c)}]
level 4	[{(a),(b),(c),(d)}]

Figure 1: Example of Leveled Division Sets

when $k_{max} > k$: ∞,

when $k_{max} = k$: $v(B_{max}, \theta_i)$,

when $k_{max} < k$: $r \times k$.

When $k_{max} > k$, it is clear that nobody wants B at this price. When $k_{max} = k$, since B_{max} is chosen so that $v(B_{max}, \theta_i)$ is maximized, the utility of agent j cannot be positive by obtaining B at this price. When $k_{max} < k$, the utility of agent j cannot be positive since $v(B, \theta_j) < r \times k$.

LDS Protocol

In the LDS protocol, the auctioneer needs to define not only the reservation price, but also the method for dividing goods into bundles. This description is called *a leveled division set.* Figure 1 shows an example of a leveled division set where there are four goods (a, b, c, and d).

Each level contains a set of divisions, where a division is a set of mutually exclusive bundles. The LDS protocol basically apply the GVA using divisions from level 1, level 2, and so on, until some agent can afford to buy a bundle by paying more than the reservation price. A leveled division set must be defined so that a union of multiple bundles in one division is always included in a division of an earlier level. For example, in level 4 of Figure 1, there is a division {(a),(b),(c),(d)}. We can see that all unions of multiple bundles, e.g., {(a,b)}, {(a,b,c)}, appear in earlier levels. This condition is required to make the protocol false-name-proof. Please consult (Yokoo, Sakurai, & Matsubara 2001b) for details of the LDS protocol.

The LDS protocol can be described as a PORF protocol. The price of bundle B for agent i is defined as follows. Assume B is included in a division of level l. If B is not included in any division, the price is ∞. Also, let us assume l_{min} represents the earliest level, where another agent wants to buy a bundle in level l_{min} by paying more than the reservation price.

when $l_{min} < l$: ∞,

when $l_{min} = l$: the price for B is determined by the same method as the GVA, where possible allocations are restricted by the divisions of level l,

when $l_{min} > l$: the reservation price.

Due to space limitations, we omit a detailed explanation, but we can show that by using this protocol description, the obtained results are identical to that by the LDS protocol presented in (Yokoo, Sakurai, & Matsubara 2001b).

False-name-proof PORF Protocol

We show that a PORF protocol is false-name-proof if the protocol satisfies following two additional conditions.

monotonic price increase: When the number of other agents increases, the price of an agent does not decrease. Formally, for any set of agent X, agent i who is not in X, and any bundle B, $P_B(\Theta_X) \leq P_B(\Theta_X \cup \{\theta_i\})$ holds.

no super-additive price increase: For any mutually exclusive bundles B, B', any set of agents X, and agents i, i' who are not in X, $P_B(\Theta_X \cup \{\theta_{i'}\}) + P_{B'}(\Theta_X \cup \{\theta_i\}) \geq P_{B \cup B'}(\Theta_X)$ holds. The first term in the left side represents the price of agent i for bundle B, the second term in the left side represents the price of agent i' for bundle B', and the right side represents the price for bundle $B \cup B'$ for agent i (or i') when agents other than i (or i') are only X.

Here, we show that a PORF protocol that satisfies the above two conditions is false-name-proof. Assume agent i uses two identifiers i, i'. If the agent obtains bundle B only with one identifier, say, i, then by the condition of monotonic price increase, the price of i for bundle B decreases or remains the same when agent i refrains from using another identifier i'.

On the other hand, if the agent obtains bundle B under identifier i and bundle B' under identifier i', by the condition of no super-additive price increase, if the agent uses a single identifier, the price of $B \cup B'$ becomes smaller than (or the same as) the sum of the prices for B and B'.

When an agent uses three or more identifiers, by using a similar argument we can show that the agent's utility increases or at least remains the same when the agent uses only one identifier.

Now, let us show that the BSO protocol satisfies these two conditions. It is obvious that the protocol satisfies the condition of monotonic price increase. For the condition of no super-additive price increase, it is clear that the condition is satisfied when $P_{B \cup B'}(\Theta_X)$ is the reservation price, since the price of a bundle is never less than the reservation price. On the other hand, if $P_{B \cup B'}(\Theta_X)$ is not the reservation price, i.e., it is larger than the reservation price, then, there exists a bundle B'' that has at least one common good with $B \cup B'$, where the size of B'' is larger than or the same as $B \cup B'$ and the evaluation value for B'' of one agent in X is larger than or equal to the reservation price. Therefore, either $P_B(\Theta_X \cup \{\theta_{i'}\})$ or $P_{B'}(\Theta_X \cup \{\theta_i\})$ becomes ∞, thus the condition of no super-additive price increase holds.

On the other hand, the GVA fails to satisfy both conditions. Therefore, as shown in (Sakurai, Yokoo, & Matsubara 1999; Yokoo, Sakurai, & Matsubara 2001b), an agent can decrease its payment by using false-names and splitting its bid.

Evaluations

We compare the obtained social surplus of the BSO protocol and that of the LDS protocol using a simulation.

For each agent i, we determine bundle B required by agent i and $v(B, \theta_i)$ by the following method.

- First, we determine k, which represents the size of bundle B, by using an exponential distribution $d_e(k) = Ce^{-pk}$ (Fujishima, Leyton-Brown, & Shoham 1999). By using this distribution, many small bundles are created. The provability that a size k bundle is created is e^p times larger than that of a size $k+1$ bundle.
- Next, we randomly choose k goods included in B and choose randomly $v(B, \theta_i)$ from within the range of $[(1-q)k, (1+q)k]$. We assume that the evaluation values of an agent are all-or-nothing, i.e., the evaluation value for a bundle that does not include all of the goods in B is 0.

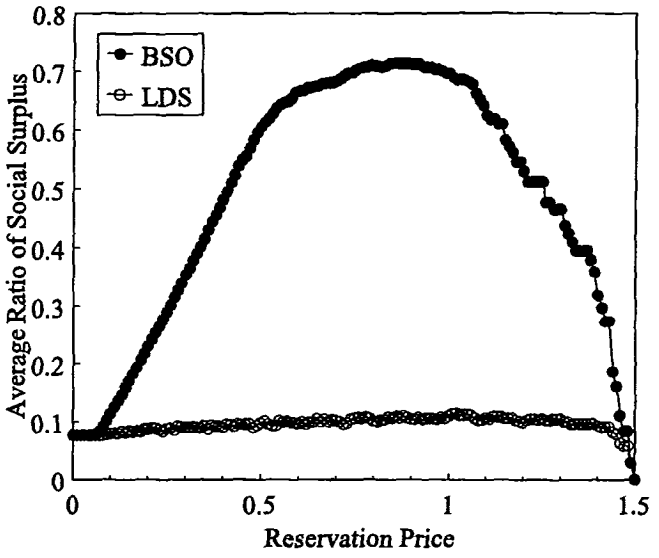

Figure 2: Comparison of Social Surplus

In the LDS protocol, the auctioneer must determine a leveled division set. In this evaluation, we construct a leveled division set similar to that in Figure 1, i.e., at level 1, we put a division that contains a single bundle of m goods. Then, at level 2, we put $m-1$ divisions, each of which contains a bundle of $m-1$ goods, and so on. More specifically, we put divisions that contain size $m-l+1$ bundles at level l. If possible, we combine multiple bundles in a single division, as shown in level 3 and level 4 in Figure 1. By using this method, we can put all small bundles in the leveled division set.

Figure 2 shows the average ratio of the obtained social surplus to the Pareto efficient social surplus by varying the reservation price. In Figure 2, we set the number of goods $m = 100$, the number of agents $n = 100$, $p = 1$, and $q = 0.5$. Each data point represents the average of 100 problem instances.

As shown in Figure 2, by setting the reservation price within the range of $[0.75, 0.98]$, the obtained social surplus of the BSO protocol can reach 70% of the Pareto efficient social surplus. On the other hand, in the LDS protocol, the obtained social surplus becomes at most 11%.

In this problem setting, most bundles consist of one or two goods, while there are a few bundles with size 7 or 8. When the reservation price is very small, both protocols sell a size m bundle to a single agent. By increasing the reservation price, the BSO protocol can allocate multiple bun-

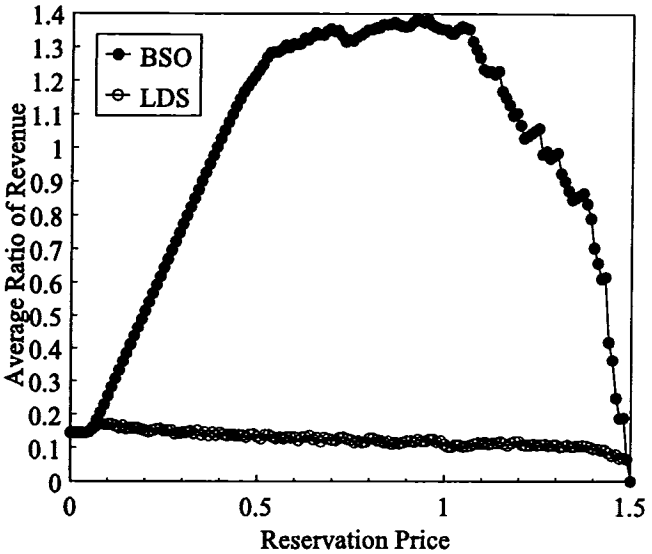

Figure 3: Comparison of Revenue

dles with different sizes to different agents. On the other hand, in the LDS protocol, even when the reservation price increases, the goods are sold at the level where bundles contain 7 or 8 goods, thus the LDS protocol can allocate only a few bundles and the obtained social surplus cannot increase very much.

Evaluations

Figure 3 shows the average ratio of seller's revenue to the revenue obtained by using the GVA assuming there exists no false-name bids. Parameter settings are identical to Figure 2. We can see that trends are almost identical to that of the social surplus, with a notable exception that the ratio can be more than 1, i.e., the BSO protocol can obtain a better revenue that that of the GVA, when the reservation prices are set appropriately.

Discussions

Designing a protocol that is guaranteed to be strategy/false-name proof has been a difficult task. If the protocol can be represented as a PORF protocol, the protocol is automatically strategy-proof. Furthermore, if the protocol satisfies additional conditions, the protocol is guaranteed to be false-name-proof.

Of course, we need to prove that a PORF protocol can obtain a feasible allocation. However, this tends to be much easier than proving a protocol is false-name-proof, since we can assume each agent declares its true type using a single identifier.

As for the computational cost of executing a protocol, a naive implementation of a PORF protocol requires calculating prices for all bundles of all agents. When the number of goods/agents becomes large, this computational cost becomes prohibitively high.

However, as in the case of the GVA, LDS, and BSO protocols, we can describe a protocol either as a PORF protocol or as the traditional manner in which an allocation of goods is determined, then the payments are calculated based on the allocation. We can assume that the description of a PORF protocol is not for an actual implementation but for a normative guideline for proving characteristics of a protocol.

As far as the authors are aware, all known false-name-proof protocols, including the IR protocol (Yokoo, Sakurai, & Matsubara 2001c) for multi-unit auctions, can be described as a PORF protocol. An interesting open question is whether any false-name-proof protocol can be described as a PORF protocol that satisfies the above additional conditions.

In comparing the LDS and BSO protocols, we can see that each protocol has its merits and demerits. In the previous section, we assume that the auctioneer does not have good knowledge of the possible evaluation values of agents. Therefore, the auctioneer must use a leveled division set that contains all possible small-sized bundles. On the other hand, when the auctioneer has good knowledge of the possible evaluation values of agents, the auctioneer can construct a more specialized leveled division set using the method described in (Yokoo, Sakurai, & Matsubara 2001a). In this case, the social surplus obtained by the LDS protocol becomes close to a Pareto efficient social surplus, which would be much better than that of the BSO protocol.

While the LDS protocol is based on the GVA, the BSO protocol is similar to a greedy protocol for *single-minded* bidders described in (Lehmann, O'Callaghan, & Shoham 1999). A single-minded bidder is an agent who is interested in only one particular bundle. In the BSO protocol, when determining the price of an agent, the protocol treats other agents as if they are a collection of single-minded bidders without considering the substitutable preferences of these agents.

Conclusions

In this paper, we introduced the concept of a Price-oriented, Rationing-free (PORF) protocol. We showed that if a protocol can be represented as a PORF protocol, the protocol is automatically guaranteed to be strategy-proof. Also, we showed that if the protocol satisfies additional conditions, the protocol is also guaranteed to be false-name-proof. We showed that existing protocols, such as the GVA and LDS, can be formalized as PORF protocols.

Furthermore, we developed a new false-name-proof PORF protocol called the BSO protocol and compared it with the LDS protocol. We showed that the BSO protocol can obtain a better social surplus and better revenue than that of the LDS protocol when the auctioneer does not have a good model of possible evaluation values of agents.

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