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Robust Double Auction Protocol against False-name bids

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Abstract

Internet auctions have become an integral part of Electronic Commerce (EC) and a promising field for applying agent technologies. Although the Internet provides an excellent infrastructure for large-scale auctions, we must consider the possibility of a new type of cheating, i.e., a bidder trying to profit from submitting several bids under fictitious names (false-name bids). Double auctions are an important subclass of auction protocols that permit multiple buyers and sellers to bid to exchange a good, and have been widely used in stock, bond, and foreign exchange markets. If there exists no false-name bid, a double auction protocol called PMD protocol has proven to be dominant-strategy incentive compatible. On the other hand, if we consider the possibility of false-name bids, the PMD protocol is no longer dominant-strategy incentive compatible. In this paper, we develop a new double auction protocol called the Threshold Price Double auction (TPD) protocol, which is dominant-strategy incentive compatible even if participants can submit false-name bids. The characteristics of the TPD protocol is that the number of trades and prices of exchange are controlled by the threshold price. Simulation results show that this protocol can achieve a social surplus that is very close to being Pareto efficient.

1 Introduction

Electronic Commerce (EC) has made rapid progress in recent years. Internet auctions have become especially popular in EC. Commercial auction sites have been very successful and continue to expand. Auction protocols can be divided into two types: one-sided auctions in which a single seller (or buyer) accepts bids from multiple buyers (or sellers), and two-sided or double auctions that permit multiple buyers and sellers to bid to exchange a designated good. For one-sided auctions, many theoretical and practical studies have been conducted [3], including those on Internet auctions and on applications of software agents [2, 9, 12].

The Internet provides an excellent infrastructure for executing much cheaper auctions with many more sellers and buyers from all over the world. However, we must consider the possibility of new types of cheating. For example, a participant may try to profit from submitting false bids made under fictitious names. Such a dishonest action is very difficult to detect since identifying each participant on the Internet is virtually impossible. We call a bid made under a fictitious name a *false-name bid*. The problems resulting from collusion have been discussed by many researchers [7, 9, 10]. Compared with collusion, a false-name bid is easier to execute since it can be done by someone acting alone, while a bidder has to seek out and persuade other bidders to join in collusion. The authors have analyzed the effect of false-name bids in one-sided auctions [8, 13] and have developed a one-sided auction protocol that is robust against false-name bids [14].

In this paper, we analyze the effect of false-name bids in double auctions[1]. Double auctions can handle situations where multiple buyers and sellers bid to exchange a designated good, and have been widely used in stock, bond, and foreign exchange markets [1, 11]. Double auctions can be either *continuous-time* or *discrete-time*. A continuous-time double auction permits exchanges at any moment during a trading period, and the overall trades of the auction are composed of multiple bilateral transactions. On the other hand, in a discrete-time auction (also called *clearing-house* or *call-market*), all traders move in a single step from the initial allocation to the final allocation. Also, the demand/supply of a buyer/seller can be either a single unit of the designated good or multiple units.

As pointed out in [5], compared with the vast amount of studies on one-sided auctions, there exists a relatively small number of research efforts on double auctions. This is be-

[1] In some double auction literature, the term *bid* only refers to a buyer's declaration, and the term *ask* is used to denote a seller's declaration. In this paper, we use the term *bid* to denote both the buyer's and seller's declarations.

cause since there exist multiple buyers and sellers, theoretical analyses become immensely complicated. For a very simple problem setting where a single unit is traded between a single buyer and a single seller (this setting is called *bilateral trade*), it has been proven that there exists no trading protocol that is *dominant-strategy incentive compatible*[2] and also satisfies *Pareto efficiency* and *individual rationality* for all cases[3] [6]. In [5], a dominant-strategy incentive compatible double auction protocol that gives up Pareto efficiency was developed. This protocol deals with the discrete-time case where each participant's demand/supply is a single unit, and it satisfies individual rationality. We call this protocol Preston McAfee's Double auction (PMD) protocol.

If we consider the possibility of false-name bids, such as a seller submitting a false-name bid by pretending to be a potential buyer, the PMD protocol is no longer dominant-strategy incentive compatible. In [14], the authors developed a one-sided, combinatorial auction protocol that is robust against false-name bids. The main idea of this protocol is to utilize the reservation prices of auctioned goods. In this paper, we present a robust double auction protocol that utilizes a concept similar to that presented in [14]. We call this protocol the Threshold Price Double auction (TPD) protocol.

In the following, we first define the basic terms used in this paper (Section 2). Next, we describe the PMD protocol (Section 3) and show examples where the PMD protocol is vulnerable against false-name bids (Section 4). Then, we describe the TPD protocol (Section 5) and show the proof that it is dominant-strategy incentive compatible (Section 6). Furthermore, we show simulation results to evaluate the social surplus obtained by using the TPD protocol (Section 7). Then, we discuss the characteristics of the TPD protocol (Section 8). Finally, we discuss a method to extend the TPD protocol to cases where the demand/supply of each buyer/seller can be multiple units (Section 9).

2 Preliminaries

In this section, we define the problem and basic terms used in this paper.

Participants: We assume there exist m buyers and n sellers. We also assume that these numbers (m and n) are not common knowledge, i.e., each buyer/seller does not know the number of buyers/sellers; thus participants can submit false-name bids. We assume a buyer x desires to have exactly one unit of the good traded in the auction[4], and his/her evaluation value of one unit of the good is represented as b^*_x. This evaluation value is private information, so the buyers/sellers other than x do not know this value. Also, a seller y has exactly one unit of the good and his/her evaluation value of one unit of the good is represented as s^*_y. This evaluation value is also private information.

Private value good: We assume that the evaluation value of each buyer/seller is independent of other participants' evaluation values. Such a good is called a *private value* good. Although participants' evaluation values might be correlated in general, the assumption of a private value good is commonly used to make theoretical analyses tractable [4, 7].

Quasi-linear utility: If a buyer x with the evaluation value b^*_x buys one unit of the good by paying the price p, we assume his/her utility is defined as $b^*_x - p$. Such a utility is called a *quasi-linear* utility [4]. Similarly, if a seller y with the evaluation value s^*_y sells one unit of the good at the price p, we assume his/her utility is defined as $p - s^*_y$. If a buyer cannot obtain a unit, or a seller cannot sell a unit, we assume his/her utility is 0.

Direct revelation mechanism: There exist many variations of possible auction protocols/mechanisms. In particular, we call the following very simple type of mechanism a *direct revelation mechanism* [4]. In a direct revelation mechanism, each buyer/seller is directly asked his/her evaluation value, and the trades and prices are determined according to the declared evaluation values.

Incentive compatibility: In a direct revelation mechanism, for each participant, if declaring his/her true evaluation value by using a single identifier (i.e., without using false-name bids) is a dominant strategy, i.e., the optimal strategy for maximizing his/her utility regardless of other participants' actions, this direct revelation mechanism is called *dominant-strategy incentive compatible* [4, 13].

If the *revelation principle* holds [4], we can restrict our attention to direct revelation mechanisms that are dominant-strategy incentive compatible without the loss of generality. 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., the combination of dominant strategies of all participants, the property can also be achieved using a direct revelation mechanism that is dominant strategy incentive compatible. The authors proved that the revelation principle still holds even if the participants can

[2] Detailed descriptions of these terms will be presented in the next section.

[3] This result can be applied to Bayesian-Nash incentive compatibility, which is a more general condition than dominant-strategy incentive compatibility.

[4] We discuss a method for relaxing this assumption in Section 9.

submit false-name bids [13]. Therefore, in the rest of this paper, we restrict our attention to direct revelation mechanisms.

If the mechanism is dominant-strategy incentive compatible, each participant of the mechanism does not need to deliberate to determine his/her strategy and can simply declare his/her true evaluation value. On the other hand, if the mechanism is not dominant-strategy incentive compatible, each participant must deliberate to determine his/her strategy by considering the number and evaluation values of other participants, and the result obtained by the mechanism becomes very difficult to predict.

Robustness against false-name bids: We say that an auction protocol is robust against false-name bids if no participant can obtain additional profit by submitting false-name bids. If such robustness is not satisfied, the auction protocol lacks incentive compatibility.

Individual rationality: If a mechanism has a dominant strategy equilibrium, and the utility of each participant is always non-negative at the equilibrium, we say that the mechanism is *individually rational* [4]. In other words, if the mechanism is individually rational, each participant never suffers any loss by participating in the mechanism. In a private value auction, individual rationality is indispensable: nobody wants to participate in an auction where he/she might be charged more money than he/she is willing to pay.

Pareto efficiency: We say that the mechanism is *Pareto efficient* if a mechanism has a dominant strategy equilibrium and the social surplus, i.e., the sum of the utilities of all participants, is maximized at the equilibrium [4]. In a more general setting, Pareto efficiency does not necessarily mean maximizing the social surplus. In an auction setting, however, participants can transfer money among themselves, and the utility of each participant is quasi-linear. Therefore, the sum of the utilities is always maximized in a Pareto efficient allocation.

Although Pareto efficiency is desirable, it has been proven that there exists no double auction protocol that is dominant-strategy incentive compatible and also satisfies Pareto efficiency and individual rationality for all cases [6]. Since individual rationality is indispensable, and we can assume a protocol is dominant-strategy incentive compatible without the loss of generality, we need to develop a double auction protocol that is dominant-strategy incentive compatible and individually rational and that can achieve a social surplus that is close to being Pareto efficient.

3 PMD Protocol

In this section, we describe the double auction protocol proposed by R. Preston McAfee [5]. We call this protocol the PMD protocol.

Let us represent declared (not necessarily true) buyers' evaluation values as $b_1, \ldots, b_m$, and declared (not necessarily true) sellers' evaluation values as $s_1, \ldots, s_n$. Furthermore, we define the order statistics to be

$$b_{(1)} \geq b_{(2)} \geq \ldots \geq b_{(m)}$$

and

$$s_{(1)} \leq s_{(2)} \leq \ldots \leq s_{(n)}.$$

Please note the reverse ordering for buyers and sellers. We use the notation (i) for the i-th highest evaluation value of buyers and the i-th lowest evaluation value of sellers[5].

Also, to simplify the protocol description, we assume $b_{(m+1)}$ denotes the lowest possible evaluation value of buyers (e.g., 0), and $s_{(n+1)}$ denotes the highest possible evaluation value of sellers (e.g., one billion dollars). Furthermore, we assume $b_{(m+1)} < s_{(n+1)}$ holds.

Let us choose k so that

$$b_{(k)} \geq s_{(k)}$$

and

$$b_{(k+1)} < s_{(k+1)}$$

hold.

Since for (1) to (k), the evaluation value of the buyer is larger than that of the seller, at most k trades are possible.

Also, we define the candidate of a trading price p_0 as follows.

$$p_0 = \frac{1}{2}(b_{(k+1)} + s_{(k+1)})$$

The protocol is defined as follows.

1. If $s_k \leq p_0 \leq b_k$ holds: the buyers/sellers from (1) to (k) trade at price p_0.
2. If $p_0 > b_k$ or $p_0 < s_k$ holds: the buyers/sellers from (1) to $(k-1)$ trade. Each buyer pays $b_{(k)}$, and each seller gets $s_{(k)}$.

If the second condition holds, since the price for buyers $b_{(k)}$ is larger than the price for sellers $s_{(k)}$, the amount $(k-1)(b_{(k)} - s_{(k)})$ is left over. We assume that the auctioneer, or the budget balancer, receives this amount. We assume that the auctioneer is a non-trading agent who does not desire to buy or sell the good.

If there exists no false-name bid, this protocol is proven to be dominant-strategy incentive compatible [5]. In this protocol, if the first condition holds, the obtained result is Pareto efficient. On the other hand, if the second condition holds, the result is not Pareto efficient since the (k)-th buyer/seller cannot trade.

[5]We assume random tie-breaking.

4 Effect of False-name Bids on PMD Protocol

In this section, we show examples where the PMD protocol is not robust against false-name bids.

Example 1 *Let us assume the true evaluation values of buyers/sellers are as follows.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 5$

If each participant truthfully declares his/her evaluation value, the first condition of the protocol holds, and buyers/sellers from (1) *to* (3) *trade at the price* $p_0 = (4+5)/2 = 4.5$. *On the other hand, if one of the sellers from* (1) *to* (3) *submits a false-name bid* 4.8 *pretending to be a potential buyer, the declared evaluation values become as follows.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4.8 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 5$

In this case, the number of trades does not change, but the price is increased to $(4.8+5)/2 = 4.9$. *We can see that a seller can increase his/her utility by submitting a false-name bid while pretending to be a potential buyer; thus the PMD protocol is not robust against false-name bids.*

Example 2 *Let us assume the true evaluation values of buyers/sellers are as follows.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 12$

If each participant truthfully declares his/her evaluation value, the second condition of the protocol holds, and buyers/sellers from (1) *to* (2) *trade, each buyer pays* 7, *and each seller gets* 4.

On the other hand, let us assume seller (3) *submits a false-name bid* 6 *pretending to be another potential seller. In this case, the declared evaluation values are as follows.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 6 < 12$

Now, the first condition of the protocol holds. Thus, the buyers/sellers from (1) *to* (3) *trade at the price* $p_0 = (4+6)/2 = 5$. *If seller* (3) *truthfully declares his/her evaluation value, he/she cannot trade and his/her utility is* 0. *On the other hand, if he/she submits a false-name bid, his/her utility becomes* $5 - 4 = 1$.

These examples show that the PMD protocol is not dominant-strategy incentive compatible when participants can submit false-name bids.

5 Robust Double Auction Protocol against False-name Bids

5.1 TPD Protocol

In this section, we present a robust double auction protocol that utilizes a concept similar to that presented in [14]. We call it the Threshold Price Double auction (TPD) protocol.

First, the auctioneer determines the *threshold price* r. As in the PMD protocol, we assume that the auctioneer is a non-trading agent who does not desire to buy or sell the good. We assume that the auctioneer determines this threshold price without consulting the declared evaluation values of buyers/sellers. Then, each buyer/seller declares his/her evaluation value[6]. Let us assume the declared (not necessarily true) evaluation values are as follows.

- buyers' evaluation values:
  $b_{(1)} \geq b_{(2)} \geq \ldots \geq b_{(i)} \geq r > b_{(i+1)} \geq \ldots$
- sellers' evaluation values:
  $s_{(1)} \leq s_{(2)} \leq \ldots \leq s_{(j)} \leq r < s_{(j+1)} \leq \ldots$

The TPD protocol is defined as follows.

1. When $i = j$: the buyers/sellers from (1) to (i) trade at the price r.
2. When $i > j$: the buyers/sellers from (1) to (j) trade. Each buyer pays $b_{(j+1)}$, each seller gets r. The auctioneer gets the amount of $j \cdot (b_{(j+1)} - r)$.
3. When $i < j$: the buyers/sellers from (1) to (i) trade. Each buyer pays r, each seller gets $s_{(i+1)}$. The auctioneer gets the amount of $i \cdot (r - s_{(i+1)})$.

5.2 Example

Example 3 *Let us assume the evaluation values are identical to Example 1.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 5$

Also, let us assume the threshold value $r = 4.5$. *In this case, if each buyer/seller declares his/her true evaluation value, the first condition of the protocol holds. Thus, the buyers/sellers from* (1) *to* (3) *trade at the price* $r = 4.5$.

If one of the sellers from (1) *to* (3) *submits a false-name bid* 4.8 *by pretending to be a potential buyer, although the*

[6] For simplicity, we assume that each buyer/seller does not know the threshold price. Although having the knowledge of the threshold price in advance will not change his/her declared value, if he/she knew that he/she had no chance to be included in the trades, he/she would not submit a bid.

price for buyers increases, the price for sellers does not change from the threshold value 4.5*; thus submitting a false-name bid is useless.*

Example 4 *Let us assume the evaluation values are identical to Example 2.*

- *buyers' evaluation values:* $9 > 8 > 7 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 12$

If the threshold price $r = 6$ *and each buyer/seller declares his/her true evaluation value, the first condition of the protocol holds; the buyers/sellers from* (1) *to* (3) *trade at the price* $r = 6$*.*

On the other hand, if the threshold price $r = 7.5$*, the third condition of the protocol holds. Thus, the buyers/sellers from* (1) *to* (2) *trade, each buyer pays the threshold price* $r = 7.5$*, and each seller gets* 4*. The seller* (3) *cannot trade even if he/she submits a false-name bid pretending to be another potential seller.*

6 Proof of Incentive Compatibility

In this section, we show the proof of the following theorem.

Theorem 1 *The TPD protocol is dominant-strategy incentive compatible even if participants can submit false-name bids.*

Since buyers and sellers are basically symmetrical, we only show the proof for the following lemma.

Lemma 1 *For a buyer, declaring his/her true evaluation value is a dominant strategy.*

We can show the fact that for a seller, declaring his/her true evaluation value is a dominant strategy in a similar way.

First, we prove the following lemma.

Lemma 2 *If a buyer submits multiple bids as buyers, his/her utility increases or remains the same if he/she submits only one bid as a buyer.*

The proof is as follows. Assume a buyer x uses two identifiers x', x'' and declares two evaluation values $b_{x'}, b_{x''}$ (we assume $b_{x'} \geq b_{x''}$). We are going to show that the utility of x increases or remains the same if x refrains from submitting the declaration $b_{x''}$.

The price for buyers is the threshold price r if the first or the third condition of the protocol holds, and $(j+1)$-th highest buyers' evaluation value if the second condition holds. Thus, if the declaration of $b_{x''}$ is not submitted, the price for buyers decreases or remains the same.

Next, we consider the number of units that x obtains when x uses two identifiers and show the proof for each of the cases.

x obtains two units: Since we assume that the demand of each buyer is only one unit, and if x refrains from submitting the declaration of $b_{x''}$, he/she can still obtain one unit, it is clear that the utility of x increases by not submitting the declaration of $b_{x''}$.

x obtains one unit: If x refrains from submitting the declaration of $b_{x''}$, x can still obtain one unit[7], and the buyers' price decreases or remains the same; thus the utility of x increases or remains the same by not submitting the declaration of $b_{x''}$.

x does not obtain a unit: If x refrains from submitting the declaration of $b_{x''}$, x still cannot obtain a unit and his/her utility remains 0.

By stating the above facts, we proved that when a buyer submits two declarations as multiple buyers, his/her utility would increase or remain the same by submitting only one declaration. Similarly, we can show that when a buyer submits more than two declarations as multiple buyers, his/her utility would increase or remain the same by submitting only one declaration. □

Next, we prove the following lemma.

Lemma 3 *In the TPD protocol, when a buyer submits a false-name bid by pretending to be a potential seller, the number of trades or the buyers' price changes only when the false-name declaration as a seller is included in actual trades.*

The proof is as follows. By adding a bid as a seller, the number of trades or the price for buyers changes only when the second condition of the protocol, i.e., $i > j$, holds. It is obvious that when $i \leq j$, i.e., when the number of sellers (whose evaluation values are smaller than the threshold price) is larger than the number of buyers (whose evaluation values are larger than the threshold price), adding a new bid as a seller changes neither the number of trades nor the price for buyers. Let us assume $i > j$ and a buyer x adds the evaluation value s_y pretending to be a potential seller. It is obvious that neither the number of trades nor the price for buyers changes unless $s_y \leq r$. However, if $s_y \leq r$, s_y will be included in the actual trades. □

In reality, x does not have a unit of the good. Therefore, when s_y is included in the actual trades, the fact that s_y is a false-name bid is brought to light. If a sufficiently large amount of penalty is imposed on a discovered false-name bidder, submitting a false-name bid as a seller is not profitable for a buyer.

There are several methods to impose such a penalty. For example, we can utilize a kind of a security deposit. If

[7] Strictly speaking, we must consider the case of random tie-breaking. However, in the random tie-breaking case, the utility of each relevant buyer is 0, even if he/she obtains one unit. Therefore, he/she is indifferent to whether he/she obtains one unit or not.

one completes his/her transaction, or his/her bid is not included in the actual trades, the security deposit would be returned. If one does not complete his/her transaction while his/her bid is included in the actual trades, the security deposit would be confiscated.

From the seller's side, a seller can submit a false-name bid by pretending to be a potential buyer, and can buy a unit if the false-name bid is included in the actual trades; thus the false-name bid will not be found. However, in this case, this seller cannot obtain a positive utility since he/she sells one unit and buys one unit, and the price for buyers is always larger than or equal to the price for sellers.

From lemmas 2 and 3, we can conclude the following lemma.

Lemma 4 *If a sufficiently large amount of penalty is imposed on a discovered false-name bidder, when a buyer submits multiple bids, his/her utility would increase or remain the same by submitting only one bid as a buyer.*

From lemma 4, we obtained that a buyer is always better off when he/she submits only one bid as a buyer. Next, we prove the following lemma.

Lemma 5 *When a buyer submits one bid as a buyer, declaring his/her true evaluation value is a dominant strategy.*

Let us assume the true evaluation value of a buyer x is b_x^*. If $b_x^* < r$, the price for buyers will never be less than r; thus trying to obtain a unit by over-reporting is useless. Also, if $b_x^* \geq r$ and x can obtain a unit when he/she truthfully declares his/her evaluation value, the price for buyers does not change by over/under-reporting as long as he/she obtains one unit; thus over/under-reporting is useless. Also, if $b_x^* \geq r$ and x cannot obtain a unit when he/she truthfully declares his/her evaluation value, then the second condition of the protocol holds, and the price for buyers is $b_{(j+1)}$. In this case, $b_{(j+1)} \geq b_x^*$ holds, and by over-reporting, the price for buyers will never be less than $b_{(j+1)}$; thus x cannot obtain a positive utility. From these facts, we conclude that truth-telling is a dominant strategy for a buyer x. □

From these lemmas, by assuming that a sufficiently large amount of penalty is imposed on a discovered false-name bidder, we can conclude lemma 1, i.e., submitting his/her true evaluation value without using false-name bids is a dominant strategy for a buyer.

7 Evaluation

In this section, we use simulation results to compare the social surplus obtained by the TPD protocol and that obtained by the PMD protocol under the assumption that participants do not submit false-name bids.

We generated a problem instance by the following method.

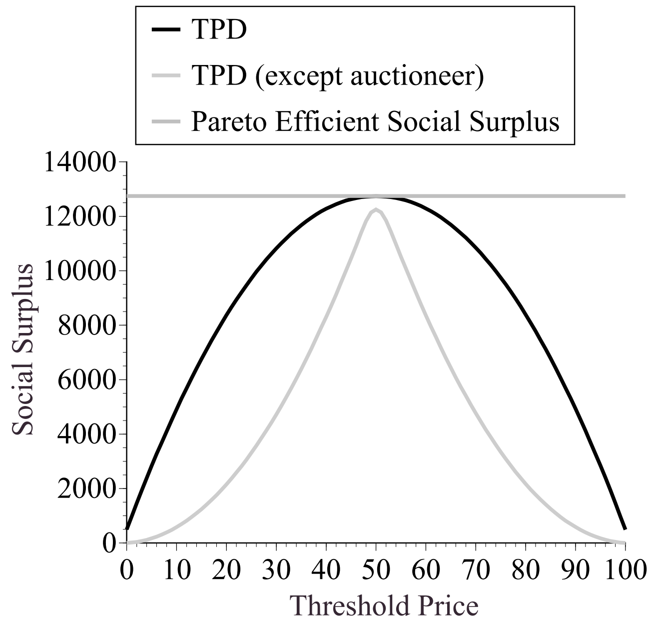

Figure 1. Social Surplus of TPD Protocol (n=500, varying threshold price)

1. Determine the number of buyers m and the number of sellers n.

2. Choose the evaluation value of each buyer/seller randomly from a uniform distribution [0,100].

In Table 1, we show the results when we set $n = m$ and vary $n(= m)$ from 5 to 500. For the TPD protocol, we set the threshold price to 50. In Table 1, we show the social surplus and the social surplus except the auctioneer. Each data point is the average of 1000 problem instances. We show the ratio to the Pareto efficient social surplus within the parentheses[8].

As shown in Table 1, when $n(= m)$ becomes large, the difference between the TPD protocol and the PMD protocol becomes relatively small, and both results become close to the Pareto efficient social surplus. The trend is similar for the social surplus except the auctioneer. When $n = m = 500$, the revenue of the auctioneer is less than 4% of the Pareto efficient social surplus.

In Figure 1, we show the results where we set $n = m = 500$ and vary the threshold price. We show the social surplus of the TPD protocol and the social surplus except the auctioneer. As shown in Figure 1, the best result is obtained when the threshold price is 50. The social surplus is relatively stable when the threshold price slightly moves away

[8] At the Pareto efficient allocation, the buyers/sellers from (1) to (k) trade as defined in Section 3.

Table 1. Comparison of Social Surplus between TPD and PMD

$n = m$	TPD	TPD except auctioneer	PMD	PMD except auctioneer
5	103.4 (92.4%)	84.4 (75.4%)	105.9 (94.6%)	96.7 (86.5%)
10	228.9 (95.9%)	187.5 (78.6%)	235.1 (98.5%)	220.5 (92.4%)
25	609.6 (98.4%)	519.9 (83.9%)	617.9 (99.7%)	599.0 (96.7%)
50	1255.9 (99.2%)	1111.4 (87.8%)	1265.7 (99.9%)	1246.5 (98.4%)
100	2533.8 (99.6%)	2314.3 (91.0%)	2543.3 (100.0%)	2527.8 (99.6%)
500	12738.3 (99.9%)	12254.1 (96.1%)	12745.5 (100.0%)	12744.9 (100.0%)

from the optimal value 50. On the other hand, the social surplus except the auctioneer is less stable compared with the social surplus including the auctioneer. When the threshold price slightly moves away from the optimal value, less valuable trades will be lost; thus the social surplus does not change very rapidly. On the other hand, the difference between the price for sellers and the price for buyers increases almost linearly when the threshold price moves away from the optimal value; thus the revenue of the auctioneer increases (and the social surplus except the auctioneer decreases) rather rapidly.

In Table 2, we show the result where n and m can be different, i.e., we randomly choose the number of buyers m and the number of sellers n from a binomial distribution $B(N, p)$, where we set $p = 0.5$. In this case, the average number of m and n is $N/2$. Other parameter settings are identical to Table 1. We can see that the results in Table 2 are very similar to the results in Table 1.

8 Discussions

As far as the authors' know, the TPD protocol is the first non-trivial double auction protocol that is dominant-strategy incentive compatible even if participants can submit false-name bids. When there exists no false-name bid, designing a dominant-strategy incentive compatible protocol is not very difficult. For example, the following simple protocol is dominant-strategy incentive compatible: we set the threshold price and determine the trades randomly from potential buyers/sellers whose evaluation values are larger/smaller than the threshold price. On the other hand, when false-name bids are possible, this simple randomization protocol is no longer dominant-strategy incentive compatible. For example, let us assume the evaluation value of a buyer is very large (e.g., $10,000), and the threshold price is small (e.g., $10). In this case, the buyer will submit multiple bids as buyers so that the chance of getting one unit increases, even if he/she needs only one unit.

One limitation of the TPD protocol is that the revenue of the auctioneer becomes large compared with the PMD protocol. This fact is not desirable for the participants of the auction. As shown in the simulation result in Figure 1, when the threshold price is set appropriately, the ratio of the auctioneer's revenue in the social surplus is small, but it can be large when the threshold price moves away from the optimal value. We need to develop a method for finding the optimal threshold price for a given situation.

Although the PMD protocol can obtain better social surplus except the auctioneer when there exists no false-name bid, the protocol does not have a dominant strategy equilibrium. Thus, each participant must deliberate to determine his/her strategy considering the number and evaluation values of other participants, and certain computational costs are required to determine his/her strategy. The outcome of the auction is very unpredictable when each participant behaves strategically. On the other hand, when using the TPD protocol, since there exists a dominant strategy equilibrium, each participant does not need to deliberate to determine his/her strategy and can simply declare his/her true evaluation value.

9 Extending Protocol to Multiple Unit Demand/Supply Cases

In this section, we discuss a method for extending the TPD protocol to cases where the demand/supply of each buyer/seller can be multiple units. Such an extension is practically important since double auctions have been widely used in stock, bond, and foreign exchange markets, and the demand/supply of each participant are usually multiple units in these markets.

The authors have shown that in one-sided auctions, the robustness of a protocol against false-name bids is affected by the marginal utilities of units. The marginal utility of a unit means the increase of the participant's utility as a result of obtaining one additional unit [4]. In [8], the authors have shown that the generalized Vickrey auction protocol [10] is robust against false-name bids when the marginal utilities of all participants decrease.

In the following, we show that a simple extension of

Table 2. Comparison of Social Surplus between TPD and PMD (Binomial Distribution)

N	TPD	TPD except auctioneer	PMD	PMD except auctioneer
10	101.3 (91.7%)	81.0 (73.3%)	103.8 (94.0%)	93.7 (84.8%)
20	223.4 (94.8%)	175.7 (74.6%)	231.2 (98.1%)	213.4 (90.7%)
50	607.0 (97.8%)	504.4 (81.3%)	618.7 (99.7%)	598.5 (96.5%)
100	1252.9 (98.8%)	1076.7 (84.9%)	1267.4 (99.9%)	1247.8 (98.4%)
200	2492.0 (99.4%)	2223.6 (88.7%)	2506.6 (100.0%)	2491.6 (99.4%)
1000	12724.0 (99.9%)	12123.9 (95.2%)	12734.9 (100.0%)	12734.4 (100.0%)

the TPD protocol satisfies incentive compatibility when the marginal utilities of all participants decrease or remain the same.

Let us represent the evaluation values of buyer x as $b_{x,1}, b_{x,2}, b_{x,3}, \ldots$, where $b_{x,k}$ represents the marginal utility of k-th unit for x. More specifically, $b_{x,k}$ represents the increase of x's utility by obtaining one additional unit when x already has $k-1$ units. Under the assumption that the marginal utilities decrease (or remain the same), for all x and k, $b_{x,k} \geq b_{x,k+1}$ holds. The assumption that marginal utilities decrease seems to be reasonable when trading stocks, bonds, or foreign currencies. Similarly, we represent the evaluation values of seller y as $s_{y,1}, s_{y,2}, s_{y,3}, \ldots$. Please note that if y has three units to sell, the minimum price at which y is willing to sell the first unit (while keeping two units at hand) is represented as $s_{y,3}$, not $s_{y,1}$. Also, the minimum price at which y is willing to sell two units can be represented as $s_{y,2} + s_{y,3}$.

Let us represent the evaluation values of each unit for buyers sorted in decreasing order as

$$b_{(1)} \geq b_{(2)} \geq \ldots \geq b_{(i)} \geq r > b_{(i+1)} \geq \ldots$$

and the evaluation values of each unit for sellers sorted in increasing order as

$$s_{(1)} \leq s_{(2)} \leq \ldots \leq s_{(j)} \leq r < s_{(j+1)} \leq \ldots,$$

where r is the threshold price.

The protocol is described as follows.

1. When $i = j$: the buyers/sellers from (1) to (i) trade at the price r for each unit.

2. When $i > j$: the buyers/sellers from (1) to (j) trade. Each seller gets r for each unit. A buyer x who obtains k units pays the total of $\sum_{l=j-k+1}^{j} max(b_{(l)}^{\sim x}, r)$, where $b_{(l)}^{\sim x}$ represents the l-th largest evaluation value except those of x. The auctioneer gets the difference.

3. When $i < j$: the buyers/sellers from (1) to (i) trade. Each buyer pays r for each unit. A seller y who sells k units gets the total of $\sum_{l=i-k+1}^{i} min(s_{(l)}^{\sim y}, r)$, where $s_{(l)}^{\sim y}$ is l-th smallest evaluation value except those of y. The auctioneer gets the difference.

Example 5 *We show an example of the protocol execution. Let us assume the evaluation values of buyers/sellers are as follows.*

- *buyers' evaluation values:* $9 > 8 > 7 > 6 > 4$
- *sellers' evaluation values:* $2 < 3 < 4 < 5 < 7$

Also, let us assume that the threshold price is 4.5*. Furthermore, buyer* x *declares both evaluation values* 9 *and* 8*, and other evaluation values belong to different sellers/buyers.*

The second condition of the protocol holds and three units are traded. Each seller gets the threshold price 4.5*. The payment of buyer* x *is calculated as follows:* $\sum_{l=3-2+1}^{3} max(b_{(l)}^{\sim x}, r) = max(b_{(2)}^{\sim x}, 4.5) + max(b_{(3)}^{\sim x}, 4.5)$*. Since* $b_{(2)}^{\sim x} = 6$ *and* $b_{(3)}^{\sim x} = 4 < 4.5$*, the payment of* x *becomes* $6 + 4.5 = 10.5$*. On the other hand, the payment of the buyer who declares* 7 *and obtains one unit is calculated as the third highest evaluation value except* 7*, i.e.,* 6*.*

With the assumption that marginal utilities decrease, if a buyer's evaluation value for the k-th unit is included in the trade, his/her evaluation value for the $k-1$-th unit is also included in the trade. Also, if a seller's evaluation value for the k-th unit is included in the trade, his/her evaluation value for the $k+1$-th unit is also included in the trade as long as the seller has the $k+1$-th unit. On the other hand, if marginal utilities of participants can increase, these properties cannot hold, and thus we cannot use this protocol since we cannot determine the trades by sorting the participants' evaluation values of each unit.

In this protocol, the procedures for determining the payments of buyers and sellers in Step 2 and Step 3 respectively are identical to the generalized Vickrey auction protocol [10]. By using the method presented in [8] for proving that the generalized Vickrey auction protocol is robust against false-name bids, we can prove that this protocol satisfies incentive compatibility.

10 Conclusions

This paper developed a new double auction protocol (TPD protocol) that is robust against false-name bids. When the participants of an auction do not submit false-name bids, the PMD protocol is proven to be dominant-strategy incentive compatible. On the other hand, if the participants can submit false-name bids, we showed that the PMD protocol is no longer dominant-strategy incentive compatible. We described the TPD protocol that utilizes the threshold price to control the number of trades and the exchange prices, and proved that this protocol is dominant-strategy incentive compatible. By using simulation results, we showed that this protocol can achieve a social surplus that is very close to the Pareto efficient social surplus.

Our future work includes extending the TPD protocol to cases where marginal utilities of units can increase and to cases where multiple goods with correlated values are traded.

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