Shill Bidding in English Auctions

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Shill bidding in English auction is the deliberate placing bids on the seller's behalf to artificially drive up the price of his auctioned item. Shill bidding has been known to occur in auctions of high-value items like art and antiques where bidders' valuations differ and the seller's payoff from fraud is high. We prove that private-value English auctions with shill bidding can result in a higher expected seller profit than first and second price sealed-bid auctions. To deter shill bidding, we introduce a mechanism which makes shill bidding unprofitable. The mechanism emphasizes the role of an auctioneer who charges the seller a commission fee based on the difference between the winning bid and the seller's reserve. Commission rates vary from market to market and are mathematically determined to guarantee the non-profitability of shill bidding. We demonstrate through examples how this mechanism works and analyze the seller's optimal strategy.

The Internet provides auctions accessible to the general public. Anyone can easily participate in online auctions, either as a seller or a buyer, and the value of items sold ranges from a few dollars to millions. To respond to this demand, online auction houses have sprung up, supported by the revenue model of charging sellers listing and commission fees. Compared to physical auctions, these listing and commissions fees are relatively small, attracting both traditional and new auction sellers. We expect online auctions will continue growing and will account for an expanding volume of economic activities.

Unfortunately, the increased popularity of online auctions has been accompanied by inevitable growing pains. According to the Internet Fraud Watch, online auction fraud has become the number one type of Internet fraud over the last three years. In 1999, it accounted for 87% of reported incidents, up from 68% in 1998. Indeed, online auctions seemed to attract fraud. Between 1998 and 1999, fraud related to auctions soared by 76% while fraud related to other types of online transactions plummeted by 44%. In the year 2000 the volume of auction fraud increased 23% and accounted for 78% of the reported incidents.

Part of the online auction fraud is due to the general "lack of trust" problem (e.g., inaccurate descriptions of goods, undelivered products, uncollectible payments, and fraudulent comments) which occurs in online fixed-price sales as well. However, the main reason why online auction attracts fraud is rooted in the uniqueness of "auctioning" over "the Internet," that is, variable pricing executed in a weakly-controlled distributed computing environment. This uniqueness brings several difficult issues, challenging the scope, validity and emphasis of the existing literature on auction theories, which currently are insufficient to guide online practices.

One of the emerging issues is shill bidding, which has become popular because of the lack of authentication over the Internet. Shill bidding is the deliberate placing of bids by the seller to artificially drive up the price of an auctioned item. The Internet environment provides unprecedented opportunities for sellers to create false identities under which to submit shill bids for their own goods in order to increase their profits. Shill bidding has been identified as one of the most common types of e-auction fraud by the Internet Fraud Complaint Center (IFCC), a partnership between the Federal Bureau of Investigation (FBI) and the National White Collar Crime Center (NW3C) (The Internet Fraud Complaint Center 2001). More than once, shill bidding in eBay has become headline news (Schwartz and Dobrzynski 2001). In addition, the analysis of the rare coin auction market in eBay also indicated that about 10% of auction buyers had shown questionable bidding behavior; they intended to run up the bid rather than to win the auction (Kauffman and Wood 2000).

Although these news and observations have triggered much concerns about shill bidding, no one has seriously examined the auction structures and policies with respect to fraud prevention and detection. As we will explain later, the pricing and auction policies of eBay actually encourage shill bidding. Another emerging issue, caused by similar reasons, is buyers' false-name bidding. False-name bidding facilitates "bid shielding" (when a buyer submits a high bid under a non-paying false identity in order to secure the buyer's low bid as the next valid bid) and also challenges the incentive compatibility of the widely practiced

Vickrey auction and its derivatives (Wang, Hidvégi and Whinston forthcoming, Wang, Hidvégi and Whinston 2001).

Our research theme is to improve or redesign online auction structures to proactively deter auction fraud. Wang et al. (2001) have designed an efficient Binary Vickrey Auction (BVA) protocol against buyer false-name bidding in multi-unit auctions. As a continuation along our research theme, this paper focuses on shill bidding.

In search for the literature on shill bidding, we found no significant discussions on this subject. Literature on auction fraud focuses mainly on buyer collusion and is quite limited. Klemperer (2000) has cautioned of the danger of the thinness of the auction-theoretic literature on auction fraud. He states that most auction literature assumes a fixed number of buyers who behave non-cooperatively and auction surveys pay relatively little attention to collusion, which is reflected by the scant literature on this important topic (Klemperer 2000). As a result, almost none has analyzed the danger of buyer-seller collusion from shill bidding.

Myerson (1981) as well as Riley and Samuelson (1981) have shown that if a certain regularity condition holds, the first and second price sealed-bid auctions and the English auction are optimal and give the same expected profit for the seller. Unfortunately, non-regular cases do occur in which these mechanisms are not optimal any more. A mechanism allowing shill bidding can give higher expected seller profit than the one against shill bidding. The reason is simple. Traditional auctions assume that the seller commits to his reserve price before an auction and does not revise it during the auction. However, with shill bidding, the seller can effectively change his reserve during the auction as he learns more about the bidders' valuations and takes advantages of this knowledge.

Such non-regular cases occur when there are different types of bidders. This is not uncommon in practice: a bidder may be either an end-user or a reseller; or in an auction with a collectible item one group of bidders thinks the auctioned item a rare original piece while another group regards it simply a copy. Hence, bidders may belong to different types. The seller does not know the exact type of a particular bidder before the auction. But during the auction, he can learn the highest bidder's type from the bids and then benefit from the knowledge.

We will introduce a Shill-deterrent Fee Schedule (SDFS) that an auctioneer can apply to charge sellers. SDFS and its parameters are designed as an incentive mechanism to discourage sellers from submitting shill bids. Under SDFS, the auctioneer still charges the seller a listing and commission fee. However, SDFS is unique in the following: 1) a listing fee is a function of the seller's reserve; 2) a commission fee is a function of the commission rate and the difference between the final sale price and the seller's reserve; and 3) the commission rate is mathematically determined to ensure the non-profitability of shill bidding. The commission rate is a function of buyers' value distribution, which differs across auction markets.

Contrast to our scheme, the existing online auction fee schedules and policies are, in fact, not designed to inhibit shill bidding, if not encouraging such practices. For instance, for a reserve price English auction, eBay charges a small listing and low commission fee. As of February 2001, for a non-featured auction, eBay's listing fee is maximum $3.30 for listing plus maximum $1.00 for refundable reserve price auction fee. The commission rates in eBay are 5% for winning bid below $25, 2.5% for $25 - $1000, and 1.25% for above $1000. For a final sale value of $10,000, the commission fee is only about $138. In auctions with high value goods, these intermediation fees are too low to deter shill bidding. As long as a seller can, from a shill, gain an extra expected profit higher than the intermediation fees he has to pay, the seller will have an incentive to conduct the fraud.

In addition, eBay's policies do not discourage shill bidding; if an item does not sell either because of no bid above the reserve or non-paying winning bidder (who may be a shill bidder), eBay allows a full or partial refund of the "final value fee credit." This means that after a period of time, the seller with shill bidding can have a second round auction of the same item at no charge. In other words, a seller anticipating a second round of free auction has less incentive to auction off his item in the first round. Although a shill seller has a lower probability to auction off the good, assuming no discount, his expected profit is not lowered because he either is better off if the shill bid pushes up the final payment or receives the same expected profit in a later round if the shill fails. But under SDFS, the seller has to pay the commission fee unless he can prove that he himself is not the non-paying winning bidder. Besides, the commission rates in different auction markets are carefully chosen by the auctioneer to ensure non-profitability from shills.

In response to the auctioneer's new SDFS fee schedule, a seller can calculate the optimal reserve price for his auctioned item, maximizing his expected profit. Both the auctioneer's optimal commission rate and the seller's optimal reserve require a knowledge of the bidders' value distribution, which, in practice, can be obtained through market research.

In this paper, we use a sample distribution to illustrate how shill bidding can be profitable in traditional English auctions and how to choose commission rates under SDFS to deter shill bidding.

Our SDFS design also indicates that a trusted third party is essential in online markets to ensure buyers the trustworthiness of the seller, and vice versa. This is not a new idea. Vickrey, in his famous paper, has suggested the use of a trustworthy bid-holder as a means to prevent shill bidding: "to prevent the use of a 'shill' (in a sealed-bid second price auction) to jack the price up by putting in a late bid just under the top bid, it would probably be desirable to have all bids delivered to and certified by a trustworthy holder, who would then deliver all bids simultaneously to the seller" (Vickrey 1961). Unfortunately, to our knowledge, there is no followup research in the auction literature extensively discussing the role of a trusted third party and its essential functions in facilitating valid and trustworthy auction transactions.

Yet the Internet demands trusted third parties to help solve the "lack of trust" problem between sellers and buyers. Therefore, departing from the traditional auction theory, we consider an auctioneer (i.e., an auction house) as an independent profit-oriented agent different from the seller. The auctioneer's goal is to maximize his profit and his income comes from the intermediation fees charged to sellers and/or the buyers. The auctioneer can attract more sellers by: 1. providing sound auction processes, 2. retaining a large buyer base, and 3. charging sellers reasonable intermediation fees. The auctioneer can attract more buyers by convincing them that the auction house provides trustable transactions and previously auctioned items are sold at reasonable prices. More sellers and more buyers increase market liquidity, beneficial not only to the auctioneer but also to sellers and buyers. Our SDFS schedule encourages honest behavior of sellers, helps to build online trust, and hence increases market liquidity.

The paper proceeds as follows. Section I intuitively discusses shill bidding and its various forms. In Section II, we theoretically analyze shill bidding under the framework of Riley and Samuelson (1981) and explain why shill bidding can provide an extra expected profit to sellers when there are multiple solutions to the equation calculating the optimal reserve. In Section III, we explain why the existing statistical and technical methods to catch shill bidders are limited and discuss the essential role of an auctioneer in deterring fraud. In Section IV, we introduce our Shill-deterrent Fee Schedule (SDFS) for English auctions, analyze its impact on sellers, and explain why it works. Section V concludes our contribution and discusses limitations and future research directions.

I. What is Shill Bidding?

Shill bidding is the deliberate placing of bids on the seller's behalf to artificially drive up the price of an auctioned item. Shill bidding occurs in second-price auctions like English and Vickrey auctions where the seller (and/or his agent(s)) pretends to be the second highest bidder and uses his bid to push up the payment of the winning bidder. In an English auction, the seller can submit a shill bid after or even before some buyer has already bid at or above the reserve (here we assume that only bids at or above the reserve price are acceptable). From the bidding process, the seller can learn about how many bidders are interested in his item and their valuations. Based on this information, the seller can make a judgment on the expected payoff of his shill bidding. By submitting shill bids, the seller can inflate the bid price, which may result in a higher final sale price for his item.

Shill bidding in English auctions is equivalent to setting up reserve price(s) dynamically during the bidding process. The auctioneer and buyers may not be aware of such an act of the seller. The buyers believe that they participate in an auction with a stable reserve, but in reality, a dynamic one adjusted according to the current bid prices.

In contrast, in a Vickrey auction, as long as bids are handled by a trusted third party to ensure that the seller has no knowledge of the bids, submitting a shill bid only achieves the same outcome as setting the reserve at the shill bid value before the auction starts. The seller's reserve has to be the single "best and final" one. Therefore, an easy solution to eliminate shills is to use sealed-bid auctions conducted by trustable auctioneers. The lack of authentication of bidders is not as big of a threat here as in an English auction.

But both sellers and auctioneers prefer English auctions because the open bidding process increases the competition among buyers. The revenue equivalence theorem only holds in a private value context, and in practice, experiences have shown that ascending auctions generate the most revenue to sellers and auctioneers (Cramton 1998). "The dynamic price discovery process of an ascending auction simply does a better job of answering the basic auction question: who should get the items and at what prices?" (Cramton 1998).

On the other hand, open-bid auctions are also attractive to buyers because their participation strategy is simple, and the open bidding procedure not only allows them to learn about other bidders' valuations but also appeals to their competitive instincts; it is not unusual in open-bid auctions to sell an item well above its reasonable price.

For the above and many more reasons, open-bid auctions are preferred in most cases, and the English auction is the most widely used online auction mechanism. Consequently, shill bidding can be widely practiced. Data collection and analysis confirms this prediction (Kauffman and Wood 2000). Although both the traditional auction houses and new cyberauction world explicitly forbid the deceptive and illegal practice of shill bidding, there is lack of theoretic work on this subject.

One of the reasons why the existing auction literature has few discussions on shill bidding is because shill bidding in physical auctions is very limited. A physical auction restricts the number of its participants. Within a small physical group, identifying each participant is easy. It is almost impossible for a seller to take a different identity as a buyer. The only way for a seller to submit a shill is to hire someone to bid on the seller's behalf. It is not only costly but also ineffective due to principle-agent problems. Because of the difficulty of conducting the fraud and the high risks invoIoved, shill bidding rarely occurs in physical auctions. But the lack of authentication in online auctions and the large number of online bidders have provided the perfect setting for easy shill bidding.

In fact, shill bidding can take several forms: I) The seller directly takes one or several buyer identities and places shill bid(s) for his own item. II) The seller hires a buyer to bid up the seller's item. III) The seller establishes a bidding ring composed of multiple buyers bidding on the seller's item, with or without the direct involvement of the seller. and IV) The sellers establishes a bidding ring composed of multiple sellers bidding on each other's items.

The collusions among the seller(s) and buyer(s), Form II, III and IV, are the original types of shill bidding in physical auctions if it ever occurs and is referred to in the auction literature. These forms of shill bidding are less effective than Form I because the seller(s) and buyer(s) often encounter the common "principle-agent" problems. Form I is the most effective and easiest way of shill bidding, especially when the anonymity of the Internet allows the seller to obtain arbitrary online identities and to orchestrate the fraud all by himself.

The security against Form I of shill bidding has to be reliable and complete. Even if we assume the really robust online authentication methods in the future and no false identity is allowed, dishonest sellers can still submit shill bids by hacking into buyers' computing systems and disguising as legitimate buyers, in which Form I transfers to Form II and III. Besides, bidding rings composed of multiple legitimate identities can also be formed. Form III and IV are more complicated and hence more deceptive.

No matter what form shill bidding takes, we expect that shill bidding will continue and increase, largely damaging the efficiency of online auction markets. Note that it is always the seller who plots behind the scenes and the ultimate goal of shill bidding is to increase the seller's profit. Hence a mechanism against shill bidding requires a redesign of the seller's incentives. In the next section, we will analyze why the seller has an incentive to shill bid in the traditional English auction. Then, we will introduce our new mechanism to modify the seller's incentive.

II. Why can Shill Bidding be Profitable in the Traditional English Auction?

In the existing literature, auctions often operate under the following *IID* assumption: 1) There is a single seller selling an item that is worth v_0 to him. 2) There are n buyers, and buyer i values the good for sale at v_i, $i = 1, \ldots, n$. and, 3) The valuation of the buyers are independent and identically distributed according to the differentiable probability distribution $F(v)$.

In many of the open auctions in the real world, assumption 3) is not true. An open auction provides each bidder a learning process and bids even in a private-value auction can often affect other bidders' valuations. Interdependent bidders' valuations can increase the effectiveness of shill bidding. Although this factor contributes to the phenomenon of shill bidding, this is a perspective that we will consider in our future research. In this paper, we retain the IID assumption and will show that shill bidding can still be a concern even in the private value model.

Let us regard the seller and buyers as risk neutral. Let $u_n(r)$ denote the seller's expected utility with n buyers and reserve price at r under the IID assumption. We add an extra $-v_0$ term to the Riley and Samuelson (1981)'s result, which gives

$$u_n(r) = v_0 F^n(r) - v_0 + n\int_r^{\infty} (F(v) + vF'(v) - 1)F^{n-1}(v)\,\mathrm{d}v \tag{1}$$

This is because we assume that the seller owns the auctioned item before the auction, which is worth v_0 to him. He either keeps the item if no bid is at or above r, or sells it to the highest bidder, which results in v_0 disutility.

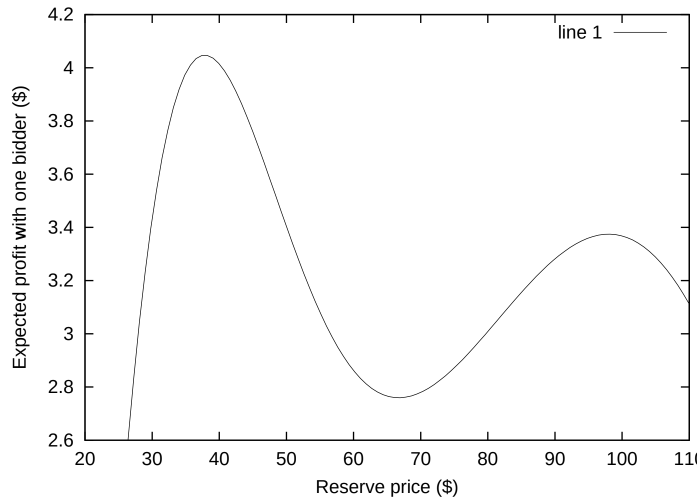

Figure 1. A case with one bidder: the seller's expected profit in the conventional English auction as a function of the reserve price if there is only one bidder. The seller's valuation is v_0 = \$20, and buyers' value distribution is $0.95N(\$20, \$20) + 0.05N(\$120, \$20)$, where $N(a, \sigma)$ denotes normal distribution. The seller's maximum expected profit is about \$4 and the corresponding optimal reserve is around \$38.

At the optimal reserve r_*, the derivative of (1) is zero, which yields the following classical result:

$$r_* = v_0 + \frac{1 - F(r_*)}{F'(r_*)} \tag{2}$$

From (2), Riley and Samuelson (1981) have argued that the seller's optimal reserve and expected profit are unique, independent of the number of buyers n. However, that is only true if (2) has a unique solution. Solutions of (2) correspond to the local minimums and maximums of the seller's expected profit given by (1). The reserve price corresponding to the local maximums does not depend on n, but the actual expected profit does change with n. As n increases, the optimal reserve corresponding to the global maximum of (1) can shift from a smaller solution to a larger solution of Equation (2).

Myerson (1981) has shown that an English auction without shill bidding is not optimal if the function $v - (1 - F(v))/F'(v)$ is not monotone increasing in v. This is exactly the case when (2) has multiple solutions. From the following example, we will show that when there are multiple solutions to (2) shill bidding can be profitable to the seller.

Figures 1, 2 and 3 illustrate an example where the seller's local maximum expected profits and the corresponding reserve prices change with the number of bidders. These curves show that the seller's maximum expected profit $u_n(r_*)$ changes with n under a sample buyers' value distribution, which is $0.95N(\$20, \$20) + 0.05N(\$120, \$20)$, where $N(a, \sigma)$ denotes normal distribution. The seller's valuation of the auctioned item is \$20. Note that each expected profit curve has two peaks. If $n \leq 11$, the seller's expected profit at the first peak is higher than the second peak and hence gives a lower optimal reserve price

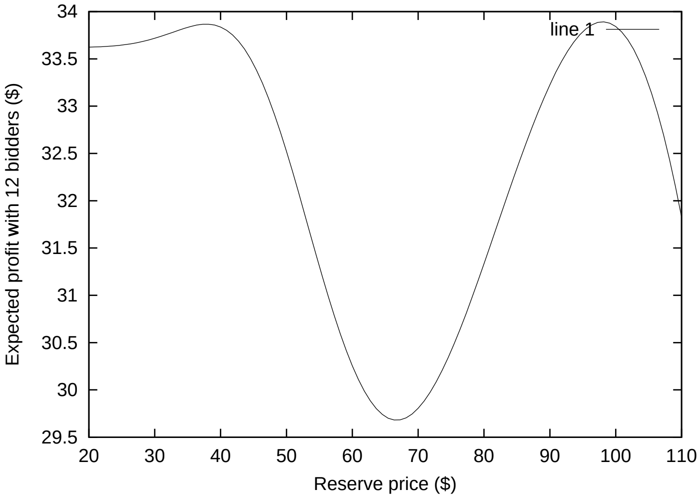

Figure 2. A case with twelve bidders: the seller's expected profit in the conventional English auction as a function of the reserve price if there are twelve bidders. The seller's valuation is v_0 = \$20, and buyers' value distribution is 0.95N(\$20, \$20) + 0.05N(\$120, \$20), where $N(a, \sigma)$ denotes normal distribution. In this case, setting reserve prices around \$38 and \$98 result in similar expected profits to the seller, which is about \$33.8.

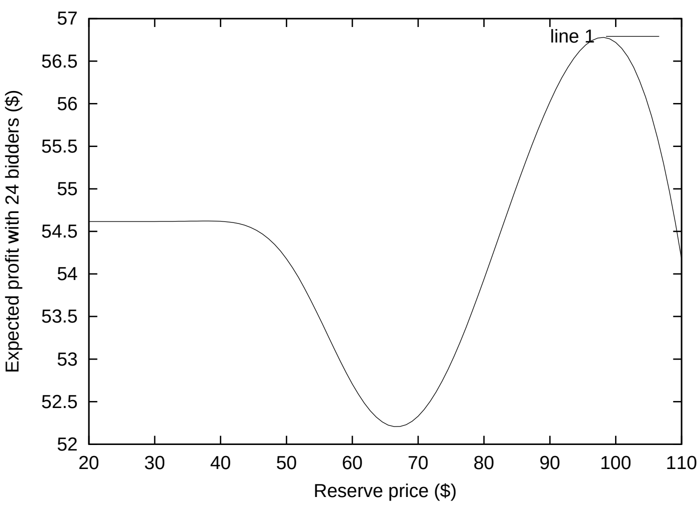

Figure 3. A case with 24 bidders: the seller's expected profit in the conventional English auction as a function of the reserve price if there are twenty four bidders. The seller's valuation is v_0 = \$20, and buyers' value distribution is 0.95N(\$20, \$20) + 0.05N(\$120, \$20), where $N(a, \sigma)$ denotes normal distribution. The seller's maximum expected profit is about \$56.7 and the corresponding optimal reserve is around \$98.

($r_* \approx$ \$38). But if $n > 12$, the optimal reserve is at the second peak ($r_* \approx$ \$98). Before the auction starts when the seller needs to set his reserve, the seller has no information about n and is uncertain about his optimal reserve. However, from the bidding, n becomes known. If shill bidding is possible, the seller's best strategy is to set the reserve corresponding to the first profit peak and then submit a shill bid corresponding to a later peak after observing enough interest in the auctioned item from the bidders during the auction process.

This example illustrates what Equation (1) represents: in the conventional English auction, a seller's expected profit is dependent on his reserve price r, the number of bidders n, and the bidders' value distribution F. Therefore, a seller can learn about n and F from the bidding process and then if necessary reset the reserve price by submitting a shill bid in order to dynamically maximize his expected profit.

Now the question is: how to set the optimal shill bid? We can simplify the problem to the case when there is only one bidder left. A seller can initially start with a low reserve and then wait for bids to stabilize. Then the seller can simply assume that there is only one bidder left and submit shills to reset his reserve. In this way, the optimal shill problem is reduced to the one bidder case. There were some highly publicized cases of shill bidding on eBay related to rare collectibles where there was only one person who really wanted to buy the collectible at all costs, and the shill bids were submitted after only that person remained to bid.

If the current high bid is b, the seller will know that the remaining bidder's valuation is drawn from the distribution F conditional on the valuation being at least b. Therefore, the cumulative probability distribution function of the high bidder is:

$$G(v) = F(v|v \geq b) = \frac{F(v) - F(b)}{1 - F(b)} \tag{3}$$

At this point, the seller has the option to set a new reserve by submitting a shill bid. He knows that there is only one bidder left, with a value distribution of G. Therefore, his expected profit with a shill bid $s \geq b$ is

$$\begin{aligned} w(s) &= (s - v_0)(1 - G(s)) = \frac{(s - v_0)(1 - F(s))}{1 - F(b)} \\ &= \frac{u_1(s)}{1 - F(b)} \end{aligned} \tag{4}$$

Here $s = b$ is equivalent to accepting the current high bid (no shill bidding). Shill bidding is profitable if, for some $s > b$, $w(s) > w(b)$, which happens if and only if $u_1(s) > u_1(b)$. The seller's best strategy is to: set the reserve price corresponding to the global maximum point of u_1 (i.e., one bidder case) before the auction starts, then observe the bidding and submit a shill bid s every time $u_1(s) > u_1(b)$ (b is the current high bid). This leads to the following theorem.

THEOREM 1: *Let r_* be the optimal reserve where u_1 takes its global maximum. Under the IID assumption, shill bidding can be profitable if and only if $u_1(s) = (s - v_0)(1 - F(s))$ has a strict local maximum for some $s > r_*$.*

PROOF. The seller can start with a lower reserve than the one corresponding to the global maximum of u_1, but this would not change the result because the strategy requires the seller submit shill bids until the global maximum is reached.

The optimal shill bids of the seller maximize $u_1(s)$ for $s \in [b, \infty)$, which means that if the seller can increase his expected profit by shill bidding, the optimal shill bid must satisfy (2). But the r_* corresponding to the global maximum point of u_1 also satisfies (2), therefore if shill bidding is profitable, then (2) must have multiple solutions. ■

Let us go back to the example of one bidder case. Figure 1 shows that for \$52 $< b <$ \$98, u_1 falls below the second peek, i.e., $u_1(b) < u_1$(\$98). It implies that if the current high bid is in that region, it will be profitable for the seller to submit a shill bid at \$98.

In summary, in the classical Riley and Samuelson (1981)'s English auction framework under the IID assumption, shill bidding can be profitable if the optimal reserve equation (2) has multiple solutions. The optimal shill bid also satisfies the optimal reserve equation.

III. The Critical Role of Auctioneers in Deterring Fraud

A. *Why the Existing Methods Fail to Catch Shill Bidders?*

Not surprisingly, because of the increasing concerns about shill bidding in online auctions, several methods have already been introduced to fight against shill bidding. But none is sufficiently effective or efficient.

One method taken by eBay is to statistically analyze the bidding records to detect shill bids and bidding rings. This method is very limited because eBay only keeps one month bidding records and there is a lack of effective fraud-hunting software. Current detection of shill bidders was often triggered by reports from bidding ring members rather than discovered by the statistical methods. In addition, some insider of eBay has indicated that eBay was not willing to spend substantially on advanced data mining software. Even eBay itself admits that its screening system is not effective enough to detect all shill bids and bidding rings. Detection is hard because shill bidders try to remain undetected and hence anonymous. The Internet makes the hiding of true identities a much easier job and consequently finding one's true identity an extremely difficult task. A lot of guess work is needed and shill bidders' behavior patterns need to be defined. For instance, Kauffman and Wood (2000) regard bidders with the following behaviors are more likely to be the shill bidders: 1) are agents of the seller, and therefore not necessarily buyers and will tend to limit their bids to a single seller or perhaps a few sellers; 2) do not want to win the auction, but rather want the winner to pay more; 3) want to avoid bidding near the end of the auction where the chance of winning is greater; and 4) bid in increments higher than average in an effort to quickly run up the bid. To find correlations among these behavior patterns, an auctioneer needs to collect detailed auction records over a long period of time. But still, strong correlations can serve as a good indicator of possible shill bidding but not as the evidence. It must be followed by thorough and costly investigation to really prosecute shill bidders.

Another method against shill bidding is to apply a software agent which automatically places a bid on a buyer's behalf just seconds before the final closing time of an auction (if the auction has the pre-determined deadline like the ones in eBay). This leaves little time for the seller to submit a shill and hence secures the legitimate bidder's winning position. However, this method assumes the ideal computing environment where every bid submitted at the final moment is accepted by the auctioneer. But the fact is, at least for now, most e-auction servers are often overloaded at the final moment of an auction. Last-minute bids have a higher probability of getting rejected or delayed; they may never reach the server or arrive only after the auction has closed. "Wait until the last minute" is always not a good idea.

From social engineering perspective, the Federal Trade Commission (FTC) has launched a campaign against online auction fraud. Its SafeBid project (Federal Trade Comission Consumer Report 2000) aims to train, educate and coordinate law enforcement agencies to detect and prosecute Internet auction fraud, including shill bidding. The FTC also provides tips for auction sellers and buyers in order to raise their awareness of e-auction fraud. These efforts are helpful to build a fraud-conscious culture but more effective weapons are still in urgent need to combat fraud.

From computer engineering perspective, Friedman and Resnick (forthcoming) proposed to apply cryptographic techniques to bind true identities with online pseudonyms. Cryptographic algorithms will strengthen online authentication and restrict users from taking multiple identities. This is a feasible approach. However, it will take a long time for the general public to accept cryptography as a daily common tool for online activities. Besides, applying cryptography is also based on the assumption that the Public Key Infrastructure (PKI), necessary for the credible use of digital signatures, is valid, efficient and legitimate. The current status of the certificate authority business is still far from living up to this standard.

Proactive methods against fraud are more effective than detective or reactive approaches. Sound trading structures are more critical than secure technical implementations. The most viable approach to shill bidding, we believe, is to design an auction structure that discourages the fraud.

B. *The Essential Role of Auctioneer to Deter Shill Bidding*

We argue that designing a sound auction structure that proactively deters fraud requires the involvement of a trusted third party, i.e., a credible auctioneer. A credible auctioneer plays an essential role to facilitate truthful auction transactions between the seller and buyers. The following scenario partially explains why this is the case. Technically, the seller can grasp buyers' general interests in his item by observing bidders' web computing behaviors during the auction. If the auction process is fully controlled by the seller himself, i.e., he has full access to the auction server and full knowledge of buyers' bidding behaviors, then the seller can know exactly and in almost real-time how many and which bidders are still downloading the web page(s) regarding his auction and remain interested in his item. So the seller can have a better prediction on the probability of his success in submitting shill bids to manipulate the remaining bidders.

In fact, if the seller has full control over his auction, he can potentially undermine many auction rules and create a variety of deceptive behavior to increase his own utility. This is possible because there is no serious reputation damage like what would have caused to a dishonest online retailer. Most online retailers in direct e-sales choose not to manipulate their transactions because their dis-credibility is easy to detect due to the simplicity of the trade: prices are fixed, contractual terms are well-defined prior to the trade, and very often only one buyer and one seller are involved in the trade. Even in bundle trading where several sellers may be involved, these coordinating sellers have often cleared trading terms and reached legal agreements in advance. On the contrarary, online auctions are much more complicated and relatively not well-defined; prices are dynamically determined and an auction process often involves an undefined scope of participants. This complexity makes it harder to detect deceptive behaviors. For instance, if a bidder realizes that she has experienced the "winner's curse," she cannot tell whether it is because she was cheated by the seller or she was simply competing against another legitimate, but strong bidder. Therefore, the auction seller can increase his profit from cheating but without necessarily damaging his reputation. Because fraud in a dynamic trading environment is much harder to detect and control than in a simple stable trading environment, an independent trusted third party is even more important to help build the trust among traders. Our following SDFS scheme is a vivid demonstration how an auctioneer can play such a role.

Despite the importance of an auctioneer, traditional auction models have ignored its essential role. Most of the existing auction theory only considers an auction as a transaction between sellers and buyers. Klemperer (1999) regards an auctioneer the same agent as a seller in his most recent guide to the auction literature. Graham and Marshall (1987) treat an auctioneer as a representative of a seller and state that "an auctioneer" (that is, the seller) often responds to the presence of (buyer) coalitions by establishing higher reserve prices. As online auction fraud becomes more and more popular and hence an auctioneer, as an economic party with self-interest, becomes more and more essential and critical in auction trades, we can no longer simplify his role and ignore his importance.

IV. Shill-deterrent Fee Schedule (SDFS)

A. *The SDFS Scheme*

In current online auctions, an auctioneer controls a seller mainly in two ways: whether or not to allow the seller to have an auction in his auction site and the intermediation fee charged to the seller. A strict control over the accessibility has a side-effect; it limits the auctioneer's profit. Besides, it is difficult to recognize who are the potential shill bidders to turn the back on. Therefore, we look into the design of fee schedules to control sellers.

Current fee structures and policies of online auction houses are not theoretically designed to deter fraud. For instance, the listing fees and commission rates charged by eBay are so low that in auctions with high value goods these intermediation fees – the seller's loss – can be easily exceeded by the seller's expected gains from shill bidding. This creates an incentive for fraud. If for a final sale of $10,000 the commission fee is only $138 rather than a higher value, say $800, a shill bid aiming to raise the final bid above $10,138 (to be exact, above $10139.87) is less risky than a shill aiming to raise the winning bid above $10,800.

One may think that an auctioneer can simply raise up the listing fees and commission rates to force shill bids to be bolder and riskier if they are expected to be profitable. But if so, the auctioneer may lose sellers to other auctioneers in the market who charge lower intermediation fees. Besides, an auctioneer should not punish honest sellers together with shill bidders. Therefore, we suggest that an auctioneer charge a variable listing and commission fees that reward honest sellers and punish dishonest ones.

Under this guidance, we design a variable intermediation Shill-deterrent Fee Schedule (SDFS). Our SDFS English auction is conducted according to the following rules:

1. The seller sets the reserve price at r. Only bids greater than or equal to r will be accepted by the auctioneer.

2. The buyer with the highest bid v ($v \geq r$) wins, and pays her bid.

3. ***SDFS****:* The seller pays the auctioneer a listing fee $(1-c)l(r)$ before the auction and a commission fee $(1-c)(v-r)$ if the item is auctioned off, where $0 \leq c \leq 1$. Hence, the seller receives a final payment of $r + c(v-r) - (1-c)l(r)$ for the auction sale. We also assume that $0 \leq l'(v) \leq 1$ for all v.

4. The seller is obligated to pay the auctioneer the commission fee even if the winning bidder does not pay, unless the seller can prove to the auctioneer that the non-paying winning bidder is not the seller himself or is not affiliated with the seller.

With these rules, shill bidding is riskier because if a shill bid wins, the seller loses not only his listing fee but also $(1-c)$ times the difference between the shill bid and reserve. If the seller announces too low a reserve price, the seller will be punished with a higher commission fee when the final sale value remains the same. If too high, the seller will be punished with a higher listing fee and a higher risk of no sale. The intricacies in SDFS English auction rules work hand in hand to encourage sellers to truthfully disclose their optimal reserves before the auction starts.

Besides, to ensure the non-profitability of shill bidding, the commission rate $(1-c)$ is carefully chosen to increase the risks from shill bidding, that is, the seller's loss from shills outweighs his possible gain. In each auction market, c varies and is mathematically determined by the characteristics of the market: the buyers' value distribution. An auctioneer would probably charge a higher commission rate in a private-value antique auction market where a shill bid is most likely to be profitable than in a common-value palm pilot auction market.

Another positive aspect of SDFS English auction rules is that they do not affect honest bidders and do not punish honest sellers. To honest bidders, the rules are the same as in a traditional English auction where the best strategy for each bidder is to raise her bid as long as it is below her valuation. To honest sellers, they can still minimize their intermediation fees because SDFS rewards their truthful disclosure of their optimal reserves. For the same sale price in the same market, SDFS charges smaller commission fees if the reserve is closer to the sale price. The $l'(v) \leq 1$ condition is also helpful here because $l'(v)$ should be small enough so that the listing and commission fees are low unless the sale price is well above the seller's reserve. If the latter case occurs, the seller would probably not mind paying higher intermediation fees out of his surprisingly high profit.

B. *Seller's Optimal Reserve Price(s) under SDFS*

To see how SDFS deters shill bidding, we need to compare the seller's expected profits with and without shill bidding under SDFS. To do so, we need to know the seller's optimal reserve price(s) under SDFS.

Let $u_n(r, c)$ denote the seller's expected profit with n buyers, reserve price r, and $0 \leq c \leq 1$. When $c = 1$, this is equivalent to Equation (1) of the classical auction, i.e., $u_n(r, 1) = u_n(r)$. After rearranging (1), we get

$$(5) \qquad u_n(r,1) = (r - v_0)(1 - F^n(r)) - r(1 - F^n(r)) + n\int_r^{\infty}(F(v) + vF'(v) - 1)F^{n-1}(v)\,\mathrm{d}v$$

The first term is the seller's expected profit if the highest bidder pays only the reserve price. The remaining terms represent the extra profit that the seller gains from the sale price above the reserve. Under the SDFS payment schedule to the seller, i.e., $r + c(v - r) - (1 - c)l(r)$, the first term in (5) does not change but the subsequent terms have to be multiplied by c and the listing fee has to be deducted, which gives

$$(6) \qquad u_n(r,c) = [(1 - c)r - v_0](1 - F^n(r)) - (1 - c)l(r) + cn\int_r^{\infty}(F(v) + vF'(v) - 1)F^{n-1}(v)\,\mathrm{d}v$$

Note that without considering the listing fee, the seller's expected profit is the convex combination of that in the all-bidder-collude auction (Graham and Marshall 1987) with weight $(1 - c)$ and that in the no-bidder-collude auction (Riley and Samuelson 1981) with weight c. In the case of all-bidder-collude, all of the n bidders agree that only one bidder will bid and act as if her valuation is the maximum of all bidders. Since there is no competition, this single bidder will get the good at the reserve price and hence the seller's profit is $(r - v_0)(1 - F^n(r)) - (1 - c)l(r)$. In the case of no-bidder-collude, the seller's expected profit is given by (1).

Differentiating (6) with respect to r, the seller's expected profit is maximized for some r satisfying the condition

$$(7) \qquad \frac{\partial u_n}{\partial r}(r,c) = (1 - c)(1 - l'(r) - F^n(r)) - nF^{n-1}(r)[F'(r)(r - v_0) - c(1 - F(r))] = 0$$

We assume now that near the optimal reserve price, $F'(r) > 0$. The only cases when this might not be true is when the commission fee and marginal listing fee are high, i.e., c is small and $l'(r)$ is large. Dividing (7) by $nF^{n-1}(r)F'(r) > 0$, we get the following result for the optimal reserve:

$$(8) \qquad \begin{aligned} r &= v_0 + c\frac{1 - F(r)}{F'(r)} + (1 - c)\frac{1 - l'(r) - F^n(r)}{nF^{n-1}(r)F'(r)} \\ &= v_0 + c\frac{1 - F(r)}{F'(r)} + (1 - c)\frac{1 - l'(r) - F^n(r)}{F^{n\prime}(r)} \end{aligned}$$

In addition, the seller's expected profit, as a function of r, is increasing if r is less than the right side of Equation (8), and is decreasing if otherwise.

Note that under the payment schedule of SDFS, Equation (8) describing the optimal reserve price r_* that maximizes the seller's expected profit is the convex combination of the all-bidder-collude case with weight $(1 - c)$ and the no-bidder-collude case with weight c. Again, when setting $c = 1$, this yields to the same result as Equation (2), the Proposition 3 in Riley and Samuelson (1981).

Also note that if there is only one buyer, i.e., $n = 1$, Equation (8) is identical to the classical auction case, since the only buyer will bid at the reserve price and this bid will win due to the lack of competition.

We can see from (8) that charging a listing fee reduces the optimal reserve price. Increase in the marginal listing fee reduces the marginal profit. To gain part of the reduction back, the seller can reduce the optimal reserve. Increase in the marginal listing fee also has an effect of reducing more of the expected profit at larger local maximum points.

C. *How to Deter Shill Bidding under SDFS?*

Now let us consider shill bidding in SDFS English auctions. The seller can observe the auction until the bidding stops, i.e., only one bidder remains and no one would outbid the current highest bid b. At this point the seller may try to push up the price by shill bidding against the remaining bidder: bid s above b until s is outbid. If the highest bidder quits before the seller does because her valuation $v < s$, then the seller wins the item at the highest bidder's valuation. Otherwise the highest bidder wins and pays the shill bid s.

Case I: The seller's shill bid is the winning bid.

The seller pays $v + (1-c)l(r)$ and receives a payment of $r + c(v-r)$. Hence, the seller's gain is

$$\begin{aligned} u_I(s,v) &= r + c(v-r) - v - (1-c)l(r) \\ &= -(1-c)(l(r) + v - r) \end{aligned} \tag{9}$$

Note that there is no v_0 in the equation because the good stays with the seller.

Case II: The seller's shill bid s is not the winning bid.

A bidder has outbid the shill and pays the second highest bid, i.e., the shill bid s. The seller pays $(1-c)l(r)$, losses the good, and receives a payment of $r + c(s-r)$. So the seller's gain is

$$u_{II}(s) = r + c(s-r) - v_0 - (1-c)l(r)$$

The conditional probability that the winning bid is above b but less than v is represented by Equation (3). Hence, $G(s)$ represents the conditional probability that the shill bid s will not be outbid by a real buyer.

Combining the above two cases, the expected utility of the seller from shill bidding in an SDFS English auction is

$$\begin{aligned} w(s) &= \int_b^s u_I(s,v)\,\mathrm{d}G(v) + (1-G(s))u_{II} \\ &= (1-G(s))(cs - v_0) + \\ &\quad (1-c)\Big[r - l(r) - \int_b^s v\,\mathrm{d}G(v)\Big] \\ &= (1-G(s))s - v_0 + G(s)v_0 \ + \\ &\quad (1-c)\Big[r - l(r) - s + \int_b^s G(v)\,\mathrm{d}v\Big] \end{aligned} \tag{10}$$

The seller's expected profit with no shill bidding is

$$w(b) = (1-c)(r - l(r)) + cb - v_0$$

Therefore, to prevent shill bidding, we need to choose some c which ensures that the seller will not earn extra profit from shill bidding, that is, $w(s) \leq w(b)$, which leads to

$$(1-G(s))(s-v_0) + v_0 - b \leq (1-c)\int_b^s (1-G(v))\,\mathrm{d}v$$

Replacing $G(s)$ with $\frac{F(s)-F(b)}{1-F(b)}$ gives

$$(1-c) \geq \frac{(1-F(s))(s-v_0) + (1-F(b))(v_0-b)}{\int_b^s (1-F(v))\,\mathrm{d}v} \tag{11}$$

Inequality (11) gives the lower bound of the commission rate $(1-c)$ above which shill bidding is non-profitable. The upper bound of the commission rate can be determined by the competition in the auctioneer market. Too high a commission rate will drive sellers to other auction markets.

Next, we simplify the determination of the lower bound of the commission rate in an auction market. We will start with a special case, then prove that the result of the special case can be generalized.

Consider one special case when s is only slightly above the current highest bid b, i.e., calculating the limit of (11) as $s \downarrow b$. This gives

$$1 - c \geq 1 - \frac{b - v_0}{1 - F(b)}F'(b) \tag{12}$$

Inequality (12) represents the lower bound of a commission rate $(1-c)$ under which a small shill bid (a shill slightly above the current high bid) is not profitable. The following theorem shows that if a reasonable commission rate is chosen according to (12) to discourage small shill bids, it also ensures that no other shill bid is profitable.

THEOREM 2: *Given b_0, shill bidding is not profitable for any $b \geq b_0$ and $s > b$ if and only if $1 - c \geq 1 - \frac{b-v_0}{1-F(b)}F'(b)$ holds for all $b \geq b_0$.*

PROOF. By contradiction. Assume that shill bidding is profitable, i.e., $w(s) - w(b) > 0$, and (12) is true for all $b \geq b_0$. This implies that $\exists b < \xi < s : w'(\xi) > 0$. Taking the derivative of (10) and using $F(b) \leq F(\xi)$, we get

$$\begin{aligned} 0 < w'(\xi) &= c\frac{1-F(\xi)}{1-F(b)} - \frac{\xi - v_0}{1-F(b)}F'(\xi) \\ &\leq c - \frac{\xi - v_0}{1-F(\xi)}F'(\xi) \end{aligned}$$

which is equivalent to

$$1 - c \leq 1 - \frac{\xi - v_0}{1-F(\xi)}F'(\xi)$$

This contradicts our hypothesis. On the other hand, if (12) does not hold for some b, then for some sufficiently small $\varepsilon > 0$, a shill bid of $b + \varepsilon$ is profitable. ■

Hence, inequality (12) is a simplified calculation for determining the lower bounds of commission rates. To find the lowest required commission rate for a particular auction market to discourage shill bidding, an auctioneer can use Theorem 2 with $b_0 = r_*$ and take the maximum of the right-hand side of (12) for all possible bids above the optimal reserve. In particular, (12) must hold for $b = r_*$, which, together with (8), implies that $l'(r_*) \leq 1 - F^n(r_*)$ must hold, i.e., the listing fee cannot be too high.

Figure 4 shows the minimum commission rate the auctioneer should charge to deter shill bidding in a particular auction market where the buyers' value distribution is $0.95N(\$20, \$20) + 0.05N(\$120, \$20)$ and the seller's valuation v_0 is \$20. Even without any commission, if the current highest bid b is between \$52 and \$66.7, a small shill bid is not profitable to the seller. \$52 is the reserve price between the two peaks of Figure 1 where the seller's expected profit starts to drop below the second peak

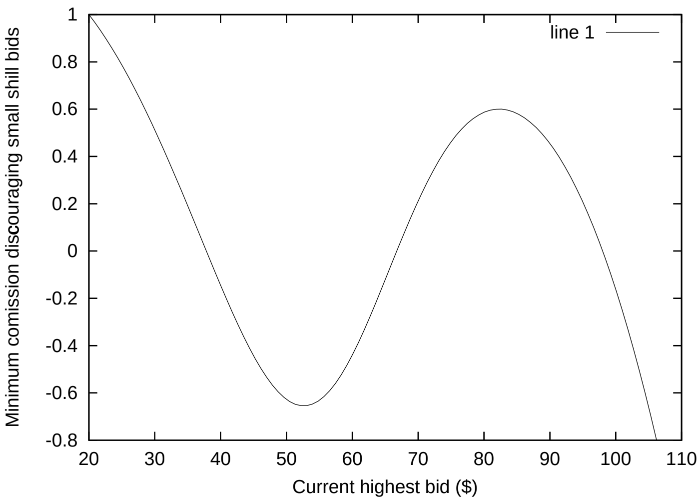

Figure 4. With the buyers' value distribution as $0.95N(\$20, \$20)$ + $0.05N(\$120, \$20)$ and the seller's valuation as v_0 = \$20, the lower bound of the commission rate $(1 - c)$ (as a function of the current highest bid) that the auctioneer must charge under SDFS to make shill bids unprofitable.

and \$66.7 is the reserve above which small shill bids become profitable, i.e., where the minimum commission rate in Figure 4 becomes positive. But as it can be calculated from (11), a bold shill bid around \$98 is profitable. However, under SDFS, if the auctioneer sets the commission rate above 60% (the maximum of all the minimum $(1 - c)$ under all possible $b \geq r_*$, $r_* \approx$ \$48 if assume ten bidders), no shill bid, small or bold, will be profitable. 60% is kind of high because Figure 4 depicts a rather extreme case where the means of the value distributions of two types of buyers are quite apart.

In most situations, a much lower commission rate should be sufficient to deter shills. Take the eBay example, if the buyers' value distribution is $0.95N(\$8700, \$400)$ + $0.05N(\$10400, \$400)$, with the seller's valuation at \$8700, the commission rate $(1 - c)$ required to deter shill bidding is only 16.9%. With this commission rate and ten bidders, the seller's optimal reserve should be set at \$9147.5. If the final sale price is \$10,000, the commission fee is only \$144, comparable to the fee charged by eBay. This shows that for honest sellers, SDFS English auctions are not more expensive than eBay auctions. However, for sellers starting with a lower reserve, say, \$5000, the commission fee would be \$845, much higher than what eBay charges.

Note that the commission rate in (12) does not depend on the listing fee. The listing fee must be paid before the auction starts. So it is not related with shill bidding. But remember, as we have discussed earlier, the listing fee in SDFS does prevent the seller from setting his optimal reserve too high.

The optimal reserve price in the classical English auction satisfies $(r_* - v_0)F'(r_*)/(1 - F(r_*)) = 1$ (a transformation of Equation (2)), which means that for $b = r_*$ the right side of (12) is 0. Moreover, $1 - (r - v_0)F'(r)/(1 - F(r)) < 0$ implies that the seller's expected profit in the no-commission case is locally decreasing as the reserve r is increasing. Assume that after some large enough r, $1 - (r - v_0)F'(r)/(1 - F(r))$ will permanently stay below 0. In fact for most common distributions this tends to negative infinity. For example, the minimum commission rate shown in Figure 4 stays negative for $r >$ \$98. Therefore, the largest solution of $1 - (r - v_0)F'(r)/(1 - F(r)) = 0$ must be a local maximum rather than minimum of the expected profit curve. Moreover, if n is large enough, this last local maximum will become a global maximum, i.e., it will be the optimal reserve price assuming there is no shill bidding. This means that if the seller chooses the largest solution of (2) as the reserve, he will not be able to submit a profitable shill bid even if there is no commission at all. This observation is important, especially for Internet auctions where the number of bidders is potentially large and can even be assumed unlimited. However, although the seller may know that the largest solution of (2) leads to his global maximum expected profit when there is no commission fee, he can still start from a lower reserve and submit shills. SDFS can be useful to make his shills unprofitable.

V. Concluding Remarks

The critical distinction between an ascending-bid English auction and a seal-bid auction is that an ascending auction provides information about the bidding to both the bidders (Cramton 1998) and the seller. This information can be used by the seller to squeeze the extra juice out of high value bidders by shill bidding. In traditional English auctions, shill bidding can be profitable if the seller's expected profit function has multiple local maximums. These multiple humps in the seller's expected profit curve are caused by different types of buyers present in an auction market. For example, in online art auctions where most of the shill bidding activities have been reported so far, there are collectors and art dealers, who have different value distribution. In California highway procurement auctions, there are bidders who have already got a large portion of their capacity committed and bid only for participation and there are bidders with little capacity committed and bid seriously for contracts (Jofre-Bonet and Pesendorfer 2000). When there are multiple humps in the expected profit curve, the global best solution of the optimal reserve varies with respect to the number of bidders and the bidders' value distribution. Sellers with shill bidding can start with low reserve, obtain bidder information by observing the bidding process, and then maximize their expected profits accordingly by resetting a higher optimal reserve through shill bids.

We handle the shill bidding problem by redesigning English auction rules. Wilson (forthcoming) has emphasized that "one purpose of market design is to eliminate loopholes in the procedural rules that might by exploited by a wily trader." One of the key elements of our market design is the introduction of an auctioneer. Different from the traditional auction literature which assumes an auctioneer the same as the seller, we model the auctioneer as an independent profit-oriented agent and emphasize his essential role in deterring fraud.

An auctioneer can control sellers' behavior through the intermediation fee schedule he charges. The auctioneer should not set the intermediation fees too low because a seller will have the incentive to submit a shill bid as long as the shill bid leads to an extra expected profit more than the intermediation fees he has to pay. On the other hand, the auctioneer should not set fees too high because a seller would then go to competing auctioneers. Besides, it is difficult to determine one or several flat rates that would be reasonable in all auction markets. This is the rationale behind which we suggest a variable intermediation fee schedule where commission rates differ in each auction market and the actual commission fees differ in each auction sales.

Under our SDFS fee schedule, the auctioneer charges the seller the intermediation fees according to the following: 1) the listing fee is a function of the seller's reserve; 2) the commission fee is a function of the commission rate and the difference between the final sale price and the reserve; and 3) the commission rate is mathematically determined to ensure the non-profitability of shill bidding; the commission rate is a function of buyers' value distribution, which differs in each auction market. With carefully-chosen commission rates, shill bidding will not provide extra profits to the seller. Although in some special cases, shill bidding in SDFS English auctions can still provide positive expected profit to the seller, it is much riskier than in traditional English auction.

SDFS is simple because it does not add cumbersome rules that restrict honest sellers' and bidders' flexibility and only requires some change on the auctioneer's side.

We will continue exploring several open questions. The following research directions also indicate the limitations of this paper. We will

- Consider the common-value case where buyers have interdependent valuations and the IID assumption does not hold.
- Look into multi-round models. McAfee and Vincent (1997) have looked at classical sequential auctions without shill bidding. This model could be extended to cover the effects of shill bidding.
- Analyze the cases with risk-averse sellers and buyers.
- Analyze how buyers calculate their expected profits considering the probability of shill bidding from the seller.
- Analyze the auctioneer market under different competition models and discuss profit-maximizing strategies for auctioneers.

It will be a long process for both shill bidding and the methods against it to evolve and improve. This paper is only the beginning of our quest to fight auction fraud.

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