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Strategic Signaling and Free Information Disclosure in Auctions

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Abstract

With the increasing interest in the role information providers play in multi-agent systems, much effort has been dedicated to analyzing strategic information disclosure and signaling by such agents. This paper analyzes the problem in the context of auctions (specifically for second-price auctions). It provides an equilibrium analysis to the case where the information provider can use signaling according to some pre-committed scheme before introducing its regular (costly) information selling offering. The signal provided, publicly discloses (for free) some of the information held by the information provider. Providing the signaling is thus somehow counter intuitive as the information provider ultimately attempts to maximize her gain from selling the information she holds. Still, we show that such signaling capability can be highly beneficial for the information provider and even improve social welfare. Furthermore, the examples provided demonstrate various possible other beneficial behaviors available to the different players as well as to a market designer, such as paying the information provider to leave the system or commit to a specific signaling scheme. Finally, the paper provides an extension of the underlying model, related to the use of mixed signaling strategies.

Introduction

Recent advances in information processing and communication technologies have given rise to the emergence of strategic information providers in Multi-agent settings. These information providers (typically referred to as *information brokers* or *experts*) are capable of disambiguating much of the uncertainty associated with the different alternatives available to agents (e.g., in search-based markets (Nahum et al. 2012; Chhabra, Das, and Sarne 2014b), online dating (Das and Kamenica 2005), e-commerce (Hajaj, Hazon, and Sarne 2015)).

One domain where the choice of the information available to the different players is of great importance is auctions. In particular, whenever the bidders' valuations of the auctioned item depend on some uncertain property of the auctioned item, e.g, its common value, the detail and completeness of the information disclosed is crucial (Johnson and Myatt 2006; Board 2009). The information disclosed to the bidders affects the identity of the winner in the auction and the auctioneer's profit. In this context, an external information provider can be of relevance, whenever the auctioneer herself does not have the information necessary to fully disambiguate the uncertainty associated with the item (e.g., does not have the specific expertise or special equipment required for generating the information) or does not want to disclose such information for her own strategic considerations. For example, an individual selling an antique she found in her attic does not necessarily have the expertise needed in order to determine its authenticity and condition. She can, however contact an expert that knows about these things in order to get this information.

Despite their importance in auctions, the study of profit-maximizing information providers in this domain has been limited, to date, to the price setting problem, i.e., the pricing of the information offered for sale (e.g., see (Sarne, Alkoby, and David 2014)). The choice of what information to disclose in auctions was studied only in the context of information available to the auctioneer that can possibly be disclosed to the bidders (Dufwenberg and Gneezy 2002; Eső and Szentes 2007; Emek et al. 2012; Miltersen and Sheffet 2012; Ganuza and Penalva 2010; Jewitt and Li 2012). The analysis of information disclosure by an external self-interested information provider entity, however, calls for a different analysis framework and may reveal much new insight. For example, it has been shown in various domains that information brokers can gain much by limiting their information offers and its accuracy (Chhabra, Das, and Sarne 2014a) or even offering some of it for free (Alkoby, Sarne, and Das 2015; Rysman 2009; Hajaj and Sarne 2014).

In this paper, we introduce a similar approach to the auction domain, focusing in extending an information provider's strategy space to include signaling that aims to selectively disclose, for free, some of the information she holds. The signal is disclosed to the auctioneer and bidders prior to making the decision of whether to purchase the information offered for sale. In doing so, the information provider, at times, fully discloses the information she holds and hence the information is not purchased. Yet, this strategy, as demonstrated in the paper, substantially improves the price the players will be willing to pay for the information in other cases, hence overall the effect on the information provider's profit is positive.

Contributions The main contribution of the paper is the demonstration that partial free information disclosure may be beneficial for the information provider, despite the counter-intuitiveness of the action. This is demonstrated by a three-party equilibrium analysis for an information-provider-based auction setting with signaling. Furthermore, we show that the benefit of the information provider is not entirely at the expense of the auctioneer. In addition we show that in various settings players may find it beneficial to pay the information provider to leave the system entirely or switch to a different strategy. Finally, the paper offers various extensions to the information provider's strategy, such as the use of mixed signaling and restricting her strategy space.

The Model

We consider a standard second-price sealed-bid (Vickrey) auction setting where bidders' private values depend on some uncertain value X pertaining to (or characterizing) the auctioned item (e.g., the number of people passing by next to an auctioned ad space).[1] The parameter X may obtain any value from a finite set X^*, where the probability it receives a value x is given by $p(x)$ ($\sum_{x \in X^*} p(x) = 1$). We will call X the state of the world.

Each bidder can be of any type T from a finite set T^*, where the probability of a bidder being of a type t is given by $q(t)$ ($\sum_{t \in T^*} q(t) = 1$). The different types are independent. An agent's type t determines its valuation of the auctioned item (i.e., its private value) for each value x that X may obtain, denoted $V_t(x)$. Finally, it is assumed that all players (information provider, auctioneer and bidders) are familiar with the distributions of X and T and the number of bidders taking part in the auction, denoted n, and that each bidder knows her own type. Similar to recent prior work (both in auctions and other domains) we assume that the uncertainty associated with the value of X can be disambiguated by some agent denoted "information provider" (Cheng and Koehler 2003; Hagiu 2004; Evans and Schmalensee 2005). The information provider can sell this information to the auctioneer. We further assume that if such information is purchased by the auctioneer, then she must reveal it to the bidders as well, e.g., as part of fair information disclosure regulations.

Unlike prior work that also used the above underlying model, our model enables the information provider, in addition to setting the price for her information providing service, to send a signal that partially reveals the information she holds. While we do not put any constraint on the signal itself (i.e., it can have any form and its content can either directly relate or have nothing to do with the actual value of X) we assume the signal becomes public domain in the sense that it is revealed both to the auctioneer and bidders. Furthermore, we assume that the information provider must publicly commit to a specific strategy.

Formally, the information provider's strategy, denoted (M, S, C), specifies a set M of possible messages, a function $S : X^* \to M$ specifying the message $S(x)$ that will be sent when the state of the world is x ($X = x$), and a function $C : M \to \mathbb{R}_+$ that specifies the price $C(m) \geq 0$ asked for revealing the true state of the world when the message is $m \in M$.

The course of the game is therefore as follows (see Figure 1 for the extensive form game representations):

- The Information provider publicly commits to a set of possible signals M, a mapping function S, and a pricing function C. The pair (M, S) will be denoted signaling scheme onward.
- The information provider learns the true state of the world and sends the appropriate signal m according to the signaling scheme she has committed to.
- The auctioneer either purchases from the information provider the information regarding to the true value of X (and truthfully discloses it to the bidders) or does not purchase it.
- Each bidder becomes acquainted with her type and places her bid.

All actions according to the above flow are publicly visible to the other players. Notice that there are several nodes in Figure 1 that are in fact in the same information set. For example, it is possible that $S(x') = S(x'')$ (where $x' \neq x''$) hence the nodes of type 3 coming out of the "not-purchase" auctioneer decisions (originating from type 2 nodes) when the information provider commits to a strategy which uses S are all part of the same information set. One important detail that is not being presented in the figure is the fact that the bidders can be of different types hence provide different bids for the same state of the world.

All players are assumed to be fully-rational self-interested agents, aiming to maximize their expected profits. The information provider's profit is her revenue from selling the information. The auctioneer's profit is calculated as her revenue from the auction (captured by the second best bid) minus the payment made to the information provider if the information is purchased. A bidders profit is the difference between her valuation of the auctioned item and her payment to the auctioneer in case of winning the auction and zero if she loses. Finally, we measure the social welfare as the sum of the auctioneer's, bidders' and the information provider's expected profits. The social welfare is also equal to the expected true valuation of the item in the eyes of the winning bidder. This is due to the fact that both the auctioneer's and the information provider's profits are exclusively based on payments made by or to the other players, thus canceled out by other players' profits, resulting in a social welfare measure that is the true valuation of the item in the eyes of the winner. This represents the efficiency of the allocation made and aligns with the way social welfare is measured in prior work, even when not considering an information provider in the model (Krishna2002 p.75-76).

[1] A specific case is where X represents the common value of the auctioned item (Jewitt and Li 2012; Goeree and Offerman 2003; Miltersen and Sheffet 2012; Klemperer 2004) and bidders' private values depend to some extent on that common value.

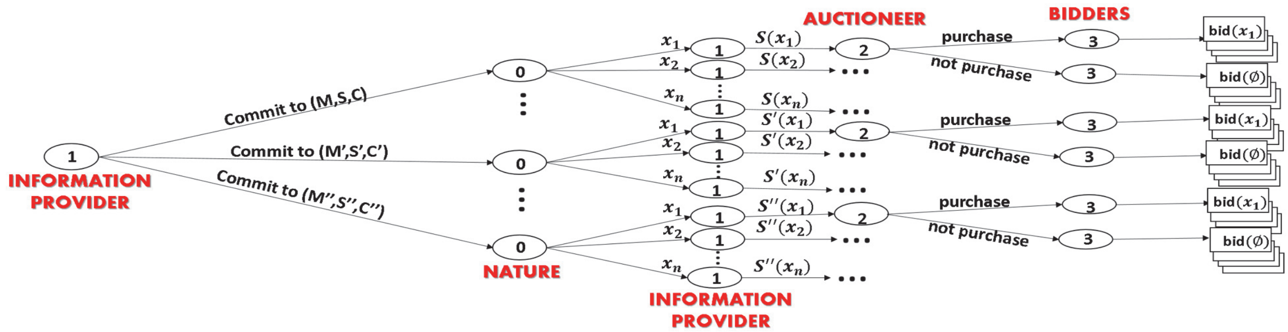

Figure 1: Extensive form game representation of the game.

Analysis

We analyze the auction using backwards induction. We start with the bidders' best response strategy. A bidder's bidding strategy is influenced by the signaling scheme to which the information provider had committed, the bidder's own type t, the signal m she disclosed or the state of the world x disclosed by the auctioneer. It is captured by the function $B_t : M \cup X^* \to \mathbb{R}$ as follows:

$$B_t(a) = \begin{cases} V_t(a) & a \in X^* \\ \sum_y p(y|a)V_t(y) & a \in M \end{cases} \tag{1}$$

where $p(x|m)$ is the conditional probability of $X = x$ given that the signal sent is m, specifically:

$$p(x|m) = \begin{cases} \frac{p(x)}{\sum_{y \in S^{-1}(m)} p(y)} & \text{if } S(x) = m \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The optimality of the above subscribed strategy derives from the fact that if the information is purchased eventually and the bidders receive the true value x, then this new information necessarily overrides any prior information encapsulated in m. Hence since this is a second price (Vickrey) auction the bidders' best response is necessarily to bid their true valuation, i.e., $V_t(x)$ (Vickrey 1961). Otherwise, if the true value is not purchased by the auctioneer (i.e., $a \in M$) then the bidders should update the probabilities assigned to each possible value $x \in X^*$: (a) each value x for which $S(x) \neq a$ obtains a probability 0 as the information provider's commitment precludes its legitimacy as a potential value X may obtain; (b) the probability of each value x for which $S(x) = a$ is the conditional probability given a, again due to the commitment of the information provider. Based on the updated (posterior) probabilities, the best response strategy is to bid the expected private value (Emek et al. 2012).

Next, we analyze the auctioneer's strategy. The auctioneer's strategy defines her action to any strategy (M, S, C) used by the information provider and the signal m sent. It needs to take into account the best response strategy of the bidders. We use the function $R_{auc} : M \cup X^* \to \mathbb{R}$ for denoting the expected profit of the auctioneer from the auction (i.e., the second highest bid) when the information provider is committed to (M, S, C) and the bidders use their best response bids. The argument of the function is the true state of the world $x \in X^*$ if the information was purchased and the signal $m \in M$ sent otherwise. The auctioneer's best response is to purchase the information whenever its value is greater than its cost. Formally, the information is purchased whenever $\sum_y p(y|m) \cdot R_{auc}(y) - R_{auc}(m) \geq C(m)$.

Now that we have the best response strategies of the auctioneer and bidders we can find an information provider's best response strategy. The information provider will choose a strategy (M, S, C) which maximizes her expected profit, given by:

$$\sum_{x \in X} p(x) \cdot C(S(x)) \tag{3}$$

where, for any $m \in M$:[2]

$$C(m) = \max(\sum_y p(y|m) \cdot R_{auc}(y) - R_{auc}(m), 0)$$

The sum (3) calculates the expected profit of the information provider when using a strategy (M, S, C) while having every element $C(S(x))$ set to be the maximum possible fee at which the information is purchased by the auctioneer whenever receiving the signal $m \in M$. The calculation sums all possible values in X^* weighing the appropriate gain according to the a priori occurrence probability of each value.

One important feature of the information provider's signaling strategy is that it induces a partition of the set X^*. Two states of the world x_i and x_j, are in the same partition element if and only if the same message is sent in both states. Clearly, the only information revealed by a message is the identity of the partition element that includes the true state of the world; the actual content is irrelevant. Therefore, there is no loss of generality in specifying a strategy as a partition of X^* and a cost c for each partition element.

[2]Note that for the case where $C(m) = 0$ (i.e., $\sum_y p(y|m) \cdot R_{auc}(y) \leq R_{auc}(m)$, hence the information has no value for the auctioneer) there is an infinite number of best-response strategies for the information provider, as any positive price will lead to the same result of not purchasing the information upon disclosing m.

This observation has two implications. The first is conceptual, as it reveals the main interpretation of the signaling - giving away information. This is further discussed in much detail in the following numerical section. The second implication is computational. Seemingly, the solution concept outlined above would require iterating over an infinite number of signaling schemes. With the observation that the information provider's signaling strategy induces a partition of X^* one needs to consider only a Bell number (of the number of values in X^*) of schemes.[3] This is still intractable when the set of possible values is large, or continuous, however in practice we typically have a very limited set of world-states (or categories). For example, a geologist selling information about the quantity of oil buried under a land will usually provide you with one out of several ranges. Similarly, the value of a rare coin offered for sale is affected by the era it was made (of a limited set).

The equilibrium can thus be calculated by finding a strategy profile in which all players are using their best response strategy. Since the information provider chooses the solution that maximizes her expected profit and we have already shown that the seemingly infinite strategy space can be reduce to a Bell number, an equilibrium solution necessarily exists.

One key feature of interest in our model where the information provider can use signaling is the change in the different players' expected profit and in particular the social welfare compared to the case where signaling is precluded. While we discuss and demonstrate numerically typical patterns of changes in the different parties' expected profit in the next section, we can also prove some relationships between the equilibrium social welfare for the two cases.

For this purpose we first define the concept of signaling refinement in the context of signaling schemes in our model, leading to a partial order of equilibria.

Definition 1 *A signaling scheme (M, S) induces a finer partition of the set X^* than the signaling scheme (M', S') if for any x the following holds: $\{y|S(y) = S(x)\} \subseteq \{y|S'(y) = S'(x)\}$ and there exists at least one x for which the inclusion is strict.*

Proposition 1 *Any equilibrium E such that there is no other equilibrium E' that uses a finer signaling scheme is efficient (maximizes the social welfare). In particular, an efficient equilibrium exists.*

Proof. It suffices to show that if there is an equilibrium by which the social welfare is not maximized then there also necessarily exists an equilibrium that uses a finer signaling scheme (hence eventually there is an equilibrium that maximizes social welfare). Consider equilibrium E by which the information provider is using a strategy (M, S, C) and the social welfare is not maximized. Since the social welfare in the auction is equal to the true valuation of the item in the eyes of the winner, the social welfare is maximized whenever the auctioned item is always allocated to the bidder that values it most. In our model this happens whenever all bidders bid their exact valuation according to the true state of the world.[4] Since the social welfare is not maximized in E then there is necessarily a signal $m \in M$ that is used in S for at least two different states of the world ($\exists x_i, x_j \in X^*$ for which $S(x_i) = S(x_j) = m$) and the information is not purchased by the auctioneer upon sending the signal m. Now consider a strategy (M', S', C') which differs from (M, S, C) only in having a different (new) signal for every state of the world for which the signal used with strategy (M, S, C) is m. The expected profit of the information provider is identical with both strategies (M, S, C) and (M', S', C') as the new signals fully disclose the corresponding states of the world and the information is not purchased in those cases. Therefore since (M, S, C) is in equilibrium, so is (M', S', C') (as it maximizes the information provider's profit). The new equilibrium uses a finer signaling scheme than the one used by E by definition. □

One important implication of Proposition 1 is that there exists at least one socially optimal equilibrium. This as opposed to the case of a model where signaling is not used at all, where it is possible that there is no positive value for the auctioneer from the information held by the information provider (hence the information is not purchased). The model where signaling is not used at all is equivalent to the case where the information provider provides an uninformative signal. An uninformative signal is one that encapsulates no information whatsoever, e.g., when always providing the same signal regardless the true world state. Therefore by enabling signaling we can guarantee at least one equilibrium with an improved social welfare, if initially the information offered no value for the auctioneer. Furthermore, the social welfare in this latter case is a lower bound for the social welfare achieved with any signaling scheme as the following proposition states.

Proposition 2 *The social welfare when the bidders do not get any signal or get an uninformative signal is lower than or equal to the social welfare in case of getting any other signal.*

Proof. The information is a random element y. (In the case of the free information (i.e., signaling), $y = S(x)$, where x is the random state of the world). For any fixed vector of bidder types, bidder i's valuation is a random variable $V_{t_i}(x)$ (as it depends on the state of the world). Given the information y, the bidder's bid is the conditional expectation of his valuation, $E(V_{t_i}(x)|y)$. The winning bid is $\max_i E(V_{t_i}(x)|y)$, which is also the conditional expectation of the social welfare, given y. The unconditional expectation is therefore:

$$E(\max_i E(V_{t_i}(x)|y)) \geq \max_i E(E(V_{t_i}(x)|y)) = \max_i E(V_{t_i}(x))$$

The expression on the right-hand side is the expected social welfare without the information y. □

[3] The number of possible partitions of a set of size b is a Bell number, given by the recursive formula: $B_{b+1} = \sum_{k=0}^{b} \binom{b}{k} \cdot B_k$, $B_0 = 1$.

[4] This can also happen when bidders bid according to expectations however there is one bidder who values the item more than others for each state of the world.

On the other hand, if the information is purchased when not using signaling then the social welfare cannot further improve with the use of signaling, as the equilibrium is already efficient.

Numerical Illustration

We continue by illustrating the benefit for the information provider in free information disclosure (i.e., signaling in our model) and the effect on social welfare and the different players' profit. Since the goal of the numerical examples is primarily illustrative, we use abstract synthetic settings where different bidder types are arbitrarily assigned their private value for any possible state of the world.

n=4		private values				
		x_1	x_2	x_3	x_4	x_5
Type	p(Values) / q(Types)	0.28	0.19	0.2	0.07	0.26
1	0.38	66	5	35	45	24
2	0.22	72	86	28	73	14
3	0.4	84	14	59	37	81

Table 1: The setting used in the example given in Figure 2

Consider the auction setting given by Table 1. In this example there are four bidders, each assigned type t_1, t_2 or t_3 with probabilities 0.38, 0.22 and 0.4, respectively. The state of the world (the value of X) may obtain one out of five possible values, x_1 through x_5, with the probabilities shown. The remaining values in the table are the private values that bidders of different types assign to the different possible values of X. In this setting, the information provider's expected profit if she decides to commit to the trivial strategy of not disclosing any information through signaling (formally: $S(x_1) = S(x_2) = S(x_3) = S(x_4) = S(x_5)$, or in the shorter form that we will use onwards: $\{\{1, 2, 3, 4, 5\}\}$), is 0 since the information is not being purchased by the auctioneer.[5] The information provider can, however, commit to a strategy $S' = \{\{1, 3, 4, 5\}, \{2\}\}$, $C(\{1, 3, 4, 5\}) = 1.24$, $C(\{2\}) = 0$, in which case the expected profit is 1.01. This example illustrates the benefit in free information disclosure. The signal results in shrinking the set of possible states of the world, hence the information provider is providing to the other players some of the information she holds, for free. This might seem somehow counter-intuitive, as potentially the information provider could have tried "selling" this information. In particular, whenever disclosing a signal m which is unique, in the sense that there is only one value $x \in X^*$ that maps to it (as in the case of x_2 in the example above), the disclosure of the signal fully reveals the true state of the world and the information provider's service is necessarily not used. Still, by distinguishing this case, the information held by the information provider in other states of the world becomes of greater value for the auctioneer and this added benefit outweighs the loss incurred by giving away part of the information for free. Specifically, in our example, the auctioneer is willing to purchase the information, whenever it is not x_2, for a payment of 1.24. This can be intuitively explained by the fact that bidders of types t_1 and t_3 (the two types associated with a substantial probability compared to t_2) have a relatively low value for x_2. In the absence of indication concerning whether or not $X = x_2$ there is a chance that if purchasing the information the value will turn to be x_2 in which case the bidders of these two types will place low bids, resulting in low expected second best bid. Therefore, while the expected second best bid for all other values will improve, the substantial decrease in profit in case the value x_2 is obtained completely precludes purchase. However, with the initial indication whether x_2 is possible or not, the auctioneer can choose to purchase the information whenever knowing that x_2 is not a possible outcome. Therefore committing to a strategy that gives away some of the information held by the information provider through signaling can be highly beneficial.

We emphasize that in a 2-player setting of an information provider and a potential buyer, where the information offered by the information provider pertains to the true state of the world, giving away free information of this kind cannot be beneficial for the information provider. The proof is similar to the one used in Proposition 2. In the model analyzed in this paper, however, the free disclosure of information through signaling influences the bids to be placed by the bidders in case the information is not purchased. This directly affects the value of information for the auctioneer and consequently her decision to purchase the information.

Figure 2 depicts the players' expected profit and the social welfare, as a function of the strategy used by the information provider for the above setting. The 52 strategies, which is the Bell number for the five values that X may obtain, are aligned along the horizontal axis according to their expected profit to the information provider (ascendingly). The bidders' expected profit in this figure is the sum of the individual expected profits weighted according to the types distribution.

As mentioned above, in Figure 2 the information is not being purchased when using the strategy $\{\{1, 2, 3, 4, 5\}\}$ and therefore the social welfare associated with this equilibrium is a lower bound to those obtained with any other strategy (see Proposition 2). The social welfare is maximized for all signaling schemes in which the true state of the world is always revealed (i.e., either when it is necessarily purchased (e.g., $\{\{1, 3, 5\},\{2, 4\}\}$), in partitions where it is either purchased or revealed through signaling (e.g., $\{\{3, 4, 5\},\{1\},\{2\}\}$) or when fully revealed through signaling (e.g., $\{\{1\},\{2\},\{3\},\{4\},\{5\}\}$). In this example, the information provider managed to generate profit through signaling, reaching an equilibrium that is not only efficient but also maximizing the bidders' expected profit. The expected profit of the auctioneer, however, actually decreased in comparison to the case where the signaling is uninformative, and the decrease is greater than the corresponding increase in the information provider's profit when switching to informative signaling. The increase in the information provider's

[5] An example where the information is being purchased even when committing to an uninformative signaling scheme is obtained by changing the value of x_1 to bidders of type t_1 in the table from 66 to 200.

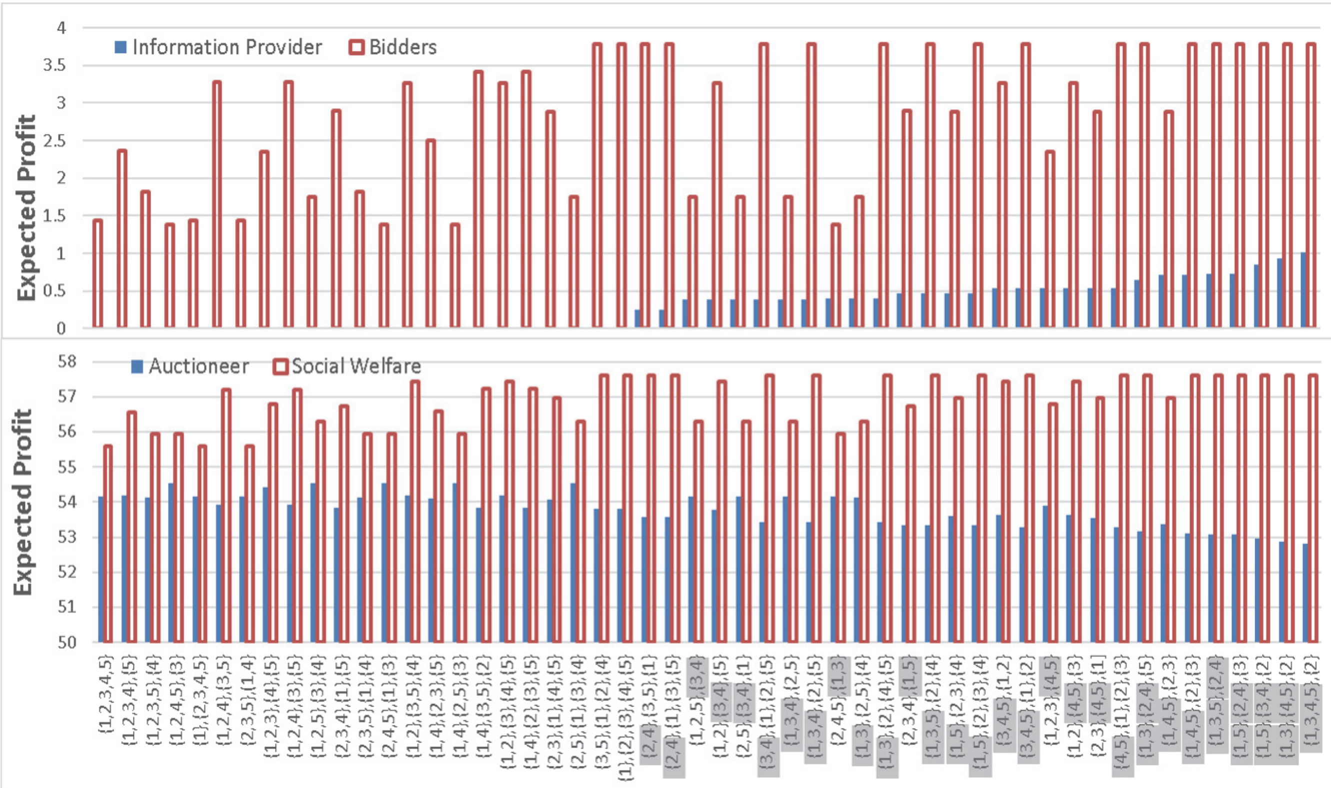

Figure 2: The players' expected profit and social welfare for the different signaling schemes the information provider can commit to. The partition elements for which the information is purchased are highlighted.

profit does not necessarily need to come fully at the expense of the auctioneer (an example for a case where the information provider's profit is higher than the auctioneer's loss can be obtained by changing the value of x_1 to bidders of type t_2 in the table from 72 to 60). This is best explained by considering the two parts in which information that affects the bidders' bids is being revealed. At the signaling stage, the information provider affects the posterior probabilities of the different values, which reflects on the bids to be placed (and hence bidders and auctioneer's expected profit) if the information is not being purchased. At this stage both the bidders' and the auctioneer's expected profit can increase or decrease. This is best illustrated by the strategies on the horizontal axis, in which the information is not being purchased, each resulting in a different profit to the different players (and, of course, a zero profit to the information provider). At the second stage, where the information can be purchased, the auctioneer's expected profit does not change, as the information provider sets the price such that she takes over whatever additional profit the new information creates for the auctioneer. The signaling scheme set by the information provider therefore controls how much she will be able to charge the auctioneer in the second part, and from the auctioneer's point of view, there is no difference between having the second phase or not.

Based on Figure 2 we can extract several benefiting behaviors available to the different players. For example, players can benefit from paying the information provider enough to leave the market completely, or, alternatively, to initially commit to a different signaling scheme which in the absence of proper compensation is not optimal. For example, the equilibrium $S = \{\{1,3,4,5\},\{2\}\}$, $C(\{1,3,4,5\}) = 1.24$, $C(\{2\}) = 0$, yields the auctioneer an expected profit of 52.8 and 1.01 to the information provider. Leaving the market (equivalent to using the strategy $\{\{1,2,3,4,5\}\}$ when the information is not purchased and no information is revealed trough signaling) yields the information provider's profit of zero, however the auctioneer's profit is 54.15. Therefore the auctioneer finds it beneficial to pay the information provider slightly over 1.01 in order to leave. Similarly, the auctioneer finds it beneficial to compensate the information provider for the decrease in her expected gain when switching from the equilibrium strategy $S = \{\{1,3,4,5\},\{2\}\}$, $C(\{1,3,4,5\}) = 1.24$, $C(\{2\}) = 0$, to strategy $S' = \{\{1,2,3\},\{4,5\}\}$, $C(\{1,2,3\}) = 0$, $C(\{4,5\}) = 1.64$, i.e., paying her slightly over 0.47 as the auctioneer's expected profit will increase, from 52.8 to 53.9.

Table 2 describes a setting where the bidders will benefit from paying the information provider to commit to a particular strategy. In this example the information provider can reach her maximal expected profit, 0.66, using twelve different strategies which among others include the strategy $S = \{\{1,3\},\{2,4\},\{5\}\}$, $C(\{1,3\}) = 5$, $C(\{2,4\}) = 2.125$, $C(\{5\}) = 0$. This strategy results in an expected

n=4		private values				
		x_1	x_2	x_3	x_4	x_5
Type	q(Types) \ p(Values)	0.3	0.3	0.21	0.1	0.09
1	0.18	96	57	46	21	41
2	0.01	69	70	86	76	2
3	0.81	72	5	9	72	14

Table 2: An example where the bidders benefit from paying the information provider to commit to a different strategy. For details see text.

profit of 3.4 for bidders. With the equilibrium strategy $S' = \{\{2,4\},\{1\},\{3\},\{5\}\}$, $C(\{1,3\}) = 8.65$, $C(\{1\}) = 0$, $C(\{3\}) = 0$, $C(\{5\}) = 0$, on the other hand, bidder's expected profit is 3.46. Therefore, the bidders will find it beneficial to pay the information provider any amount smaller than 0.06 in order to make her choose the latter strategy.

Players can also benefit from constraining the information provider's signaling scheme. Up until now, we assumed the information provider may use any signal. In many cases, however, it is possible that the information provider is limited to (or intentionally chooses (and commits to) limit herself to) a certain subset of possible signals. For example, the information provider may be limited only to signals that partition X^* into two subsets (e.g., providing only signals of the form "greater than w" or "lower than w"). Obviously such a restriction cannot improve the information provider's profit as she uses the expected-profit-maximizing strategy anyhow. A constraint over the information provider's strategy space can, however, be beneficial for the other players, and therefore a market designer may find constraining signaling to specific schemes to be appealing. For example, consider the setting used for Figure 2. Here, there are some strategies (e.g., $S = \{\{2,4\},\{3,5\},\{1\}\}$, $C(\{2,4\}) = 0.96$, $C(\{3,5\}) = 0$, $C(\{1\}) = 0$) for which the auctioneer's expected profit increases at the expense of the information provider's expected profit, while bidders' expected profit and the social welfare remain the same (all compared to the equilibrium strategy in the non-restricted scenario). Similar examples where strategy restriction can benefit also the bidders and the social welfare can be produced.

Additional interesting phenomenon is related to the effect of an increase in the number of bidders over the information provider's expected profit. Generally, one would expect the information provider's expected profit to increase as the number of bidders increases. This is because by purchasing the information the auctioneer guarantees that the bidders who value the item most will bid their true valuation. Having more bidders thus should increase the profit for the auctioneer, as it is more likely to have more bidders who assign high values to each state of the world. Since the information provider takes over a substantial portion of the auctioneer's surplus from purchasing the information we expect the information provider's expected profit to increase as a function of the number of bidders taking part in the auction, as well. The following example, however, illustrates that this is not necessarily the case. Assume there exists a type who will bid high value regardless of the state of the world. In such a case, as the number of bidders rise, so is the probability that there will be two bidder from this type participating in the auction. The auctioneer will thus profit no matter what is the true state of the world and therefore will not be interested in purchasing the information from the information provider.

Mixed Signaling

The information provider can further improve her profit through the use of mixed signaling strategies. In this case the information provider's strategy specifies a set M of possible messages, a stochastic matrix $A_{|X^*|\times|M|}$, where $A[i,j]$ is the probability that the signal being sent is $m_j \in M$ if the state of the world is $x_i \in X^*$ ($\sum_j A[i,j] = 1$), and a function $C : M \to \mathbb{R}_+$ that specifies the price $C(m) \geq 0$ asked for revealing the true state of the world when the message is m. Unlike the case of committing to a pure strategy, here a strategy does not induce a partition of the set X^* and the information revealed by a message does not necessarily disclose the identity of a subset of X^* that includes the true state of the world. Instead, the message m leads to the posterior probabilities of any of the values in X^*, according to a modification of (2)

$$p(x_i|m_j) = \frac{A[i,j]p(x_i)}{\sum_k p(x_k)A[k,j]} \quad (4)$$

We illustrate the potential benefit of using mixed signaling by the setting described by Table 3. The maximum expected profit the information provider can achieve through a pure signaling strategy is 1.4 (obtained with the strategy $S = \{\{1,3,4\},\{2,5\}\}$, $C(\{1,3,4\}) = C(\{2,5\}) = 1.4$). Now consider an alternative mixed strategy that uses $M = (m_1, m_2)$, $C(m_1) = C(m_2) = 1.43$ and $A = [(0,1),(1,0),(0,1),(0.1,0.9),(1,0)]$. This means that whenever the state of the world is x_1 or x_3, the information provider uses the signal m_2, whenever it is x_2 or x_5 the information provider uses the signal m_1, and in case the state of the world is x_4, the information provider mixes between the signals m_1 and m_2 with probabilities 0.1 and 0.9, respectively. This strategy improves the expected profit of the information provider to 1.43.

n=4		private values				
		x_1	x_2	x_3	x_4	x_5
Type	q(Types) \ p(Values)	0.07	0.14	0.25	0.28	0.26
1	0.24	32	53	9	11	14
2	0.41	68	50	19	50	15
3	0.28	5	85	56	93	70
3	0.07	58	82	88	99	0

Table 3: An example where the information provider benefits from using mixed signals. For details see text.

Related Work

Auctions focus much interest in research, mostly due to their advantage in effectively extracting bidders' valuations and the guarantee of many auction protocols to result in efficient allocation (Juda and Parkes 2009; Hajiaghayi et al. 2005; Dobzinski and Nisan 2010; Bredin, Parkes, and Duong 2007; David, Azoulay-Schwartz, and Kraus 2006; Sarne and Kraus 2005). The case where there is some uncertainty associated with the value of the auctioned item is quite common in auctions literature. Most commonly it is assumed that the value of the auctioned item is unknown to the bidders at the time of the auction and bidders may only have an estimate or some privately known signal, such as an expert's estimate, that is correlated with the true value (Goeree and Offerman 2003; Klemperer 2004; Schwartz and Kraus 1997). Many of the works using uncertain common value models assumed asymmetry in the knowledge available to the bidders and the auctioneer regarding the auctioned item, typically having sellers more informative than bidders (Akerlof 1970; Emek et al. 2012). As such, much recent emphasis was placed on the role of information revelation (Dufwenberg and Gneezy 2002; Eső and Szentes 2007; Ganuza and Penalva 2010; Jewitt and Li 2012) and corresponding computational aspects (Emek et al. 2012; Miltersen and Sheffet 2012; Dughmi, Immorlica, and Roth 2013). Still, all these works either assumed the auctioneer necessarily obtains the information (or initially holds it) or, in case considering an information provider (e.g., (Sarne, Alkoby, and David 2014; Alkoby, Sarne, and David 2014)), have not taken the information provider to be strategic or limited her strategic behavior to price-setting only. Our model uses an augmented information provider's strategy which enables a priori revelation of some of the information for free through the notion of signaling. This adds much to the complexity of the analysis as now both the auctioneer and bidders need to take into consideration the strategic behavior of the information provider.

Models where agents can disambiguate the uncertainty associated with the opportunities they consider exploiting through the purchase of information have been studied in several other multi-agent domains, e.g., in optimal stopping domains (Wilson, Szechtman, and Atkinson 2011; Azoulay-Schwartz, Kraus, and Wilkenfeld 2004). Here, the main questions studied were how much costly information it makes sense to acquire before making a decision (Moscarini and Smith 2003), in particular when additional attributes can be revealed at certain costs along the search path (Lim, Bearden, and Smith 2006; Wiegmann, Weinersmith, and Seubert 2010). Relaxation of the perfect signals assumption has also been explored in models of two-sided search (Das and Kamenica 2005). Alas, the entities providing the information in such models usually take the form of matchmakers rather than information brokers. Those that do consider a self-interested information broker in these domains, e.g., Nahum et al.(2012), focused on the way she should set the price for the information she provides and did not consider the option of free information disclosure (Hajaj and Sarne 2014). Our recent work in this area has suggested an information provider that can provide the true value of an opportunity for free, for some of the signals, showing that such strategy can benefit the information provider (Alkoby, Sarne, and Das 2015). Nevertheless, the source of the achieved improvement in the information provider's profit is completely different than in our case—the free information was shown to push users to become more picky hence increased the overall search period and consequently the number of times the information provider's service was required. In contrary, in our case the value derives from the fact that the value of the remaining information held, and consequently the expected profit, increases. Naturally the model and analysis of these two cases are substantially different. Other justifications for free information disclosure mentioned in prior work are increasing user loyalty and attracting potential users (Rysman 2009).

Discussion, Conclusions and Future Work

The analysis provided in the paper enables demonstrating that by augmenting the information provider's strategy to include signaling she can increase her expected profit. Through the use of signaling the information provider imposes herself on the auctioneer such that the information she holds is actually being purchased even in cases where it cannot be sold otherwise. The importance of this finding is in its non-intuitiveness as the essence of the signaling is free disclosure of some of the information held by the information provider.

The transition to a signaling-based strategy in real-life domains does not require much, given the so many channels available nowadays for disseminating information, like setting up a web-page. In fact, it is almost impossible to prevent such a strategic behavior and therefore this should be taken into consideration by the auctioneer and bidders when setting their strategies, making our model a realistic one.

We note that, much like in prior related work, the decision regarding purchasing the information is exclusively the auctioneer's. This holds in some real-world situations, e.g., when the information provider's services might require direct access to the auctioned item or some information that the auctioneer holds. Still, we can envision settings where the bidders are also capable of purchasing the information. Solving for the case where the information can be sold also to bidders requires, however, making many further modeling choices. For example, can the information be sold to more than a single bidder? Will the auctioneer be able to purchase the information? Will those purchasing the information be able to disclose it to any of the other players? Will the other players know of those who purchased the information? Will the information be offered for sale sequentially or to all players in parallel? Can the information provider set a different price for different players (e.g., to the auctioneer and to the bidders)? All these will certainly affect the analysis and the nature of the dynamics formed. Finally we suggest for future research the study of multi-information-provider competition which can benefit much from the analysis provided in the paper.

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