Strategy-Proof and Non-Wasteful Multi-Unit Auction via Social Network

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Abstract

Auctions via social network, pioneered by Li et al. (2017), have been attracting considerable attention in the literature of mechanism design for auctions. However, no known mechanism has satisfied strategy-proofness, non-deficit, non-wastefulness, and individual rationality for the multi-unit unit-demand auction, except for some naïve ones. In this paper, we first propose a mechanism that satisfies all the above properties. We then make a comprehensive comparison with two naïve mechanisms, showing that the proposed mechanism dominates them in social surplus, seller’s revenue, and incentive of buyers for truth-telling. We also analyze the characteristics of the social surplus and the revenue achieved by the proposed mechanism, including the constant approximability of the worst-case efficiency loss and the complexity of optimizing revenue from the seller’s perspective.

1 Introduction

Auction theory has attracted much attention in artificial intelligence as a foundation of multi-agent resource allocation. One of the mainstreams in the literature is analyzing auctions from the perspective of mechanism design. In particular, several works studied how to design strategy-proof auctions, which incentivize each buyer to truthfully report her valuation function, regardless of the reports of the other buyers. One critical contribution in the literature is the development of the Vickrey-Clarke-Groves mechanism (VCG), which satisfies strategy-proofness and various other properties (Vickrey 1961; Clarke 1971; Groves 1973).

Li et al. (2017) proposed a new model of auctions, in which buyers are distributed in a social network and the information on the auction propagates over it. Utilizing a social network, the seller can advertise the auction to more potential buyers beyond her followers, as many works studied in network science (Emek et al. 2011; Borgatti et al. 2009; Jackson 2008; Kempe, Kleinberg, and Tardos 2003). From the buyers’ perspective, however, forwarding the information increases the number of buyers, which reduces the possibility that they will get the item. Therefore, the main challenge in the auction via social network is how to incentivize buyers to forward the information to as many followers as possible, as well as truthfully reporting their valuation functions. For selling a single unit of an item, Li et al. (2017) developed an auction mechanism in which each buyer is incentivized to forward the information to her followers.

Zhao et al. (2018) studied a multi-unit unit-demand auction via social network, where each unit is identical and each buyer requires a unit. They proposed the generalized information diffusion mechanism (GIDM) and argued that it is strategy-proof. However, Takanashi et al. (2019) pointed out an error in their proof and argued that GIDM is not strategy-proof. They also proposed a strategy-proof mechanism for the same model, which however violates a revenue condition called non-deficit, i.e., the seller might suffer a deficit. To the best of our knowledge, for the multi-unit unit-demand auction via social network, no mechanism satisfying both strategy-proofness and non-deficit has been developed, except for some naïve ones.

The main objective of this paper is to propose a mechanism that satisfies both strategy-proofness and non-deficit, as well as some other properties. As Takanashi et al. (2019) pointed out, no mechanism satisfies those properties and Pareto efficiency, i.e., maximizing the social surplus, under certain natural assumptions. They thus considered weakening the non-deficit condition. In this paper, on the other hand, we consider a weaker efficiency property called non-wastefulness, which only requires the allocation of as many units as possible. Non-wastefulness has its own importance in practice. For example, in a spectrum auction, it is important to allocate as much frequency range as possible to carriers in order to guarantee a sufficient number of services.

We propose a new mechanism, called distance-based mechanism, for a multi-unit unit-demand auction via social network, which satisfies strategy-proofness, non-deficit, non-wastefulness, and individual rationality, i.e., no buyer receives negative utility under truth-telling, and whose description is much simpler than GIDM. It is inspired by the concept of the diffusion critical tree, originally proposed in Li et al. (2017), which specifies, for each buyer i, the set of critical buyers for i’s participation. If a buyer j is critical for another buyer i’s participation, i.e., if i cannot participate in the auction without j’s forwarding of information, j must
receive a higher priority in the competition.

We then make a comprehensive comparison with two naïve mechanisms that also satisfy (most of) the above properties. One is based on VCG, being applied only to the buyers who are directly connected to the seller. The other mechanism simply allocates the units in the first-come-first-served manner with no payment. We show that the distance-based mechanism dominates both of these naïve ones in terms of social surplus and the seller’s revenue. Furthermore, in those mechanisms, hiding the information, combined with reporting the true value, is also a dominant strategy, while this is not the case in our mechanism when \( k \geq 2 \). This indicates that each buyer has a stronger incentive for truth-telling in the distance-based mechanism.

We further analyze the characteristics of the social surplus and the revenue of the distance-based mechanism. About social surplus, it guarantees that each winner is in the set of top-\( k \) buyers except for her followers. It also has a constant worst-case efficiency loss, based on a measure proposed by Nath and Sandholm (2018), when an optimal reserve price is introduced. About revenue, we show that a revenue monotonicity condition fails and that maximizing revenue by optimally sending the information is NP-complete.

## 2 Preliminaries

We first define the standard notations for multi-unit unit-demand auctions. Let \( s \) be a seller who is willing to sell the set \( K \) of \( k \) identical units. Let \( N \) be the set of \( n \) buyers, where each buyer \( i \in N \) has a unit-demand valuation function for \( K \). Let \( x = (x_i)_{i \in N} \subset \{0, 1\}^n \) be an allocation, which specifies who obtains a unit, where \( x_i = 1 \) indicates that buyer \( i \) obtains a unit under allocation \( x \), and \( x_i = 0 \) otherwise. Next, we define additional notations for the auction via social network. For each buyer \( i \in N \), let \( r_i \subseteq N \setminus \{i\} \) be the set of buyers to whom buyer \( i \) can forward the information, called \( i \)'s followers. Also, let \( r_{N} \subseteq N \) be the set of direct buyers, i.e., those to whom the seller \( s \) can directly send the information. Given \( (r_i)_{i \in N} \setminus \{s\} \), we define the auction network as a digraph \( G = (N \cup \{s\}, E) \), where for each \( i \in N \cup \{s\} \) and each \( j \in r_i \), a directed edge, from \( i \) to \( j \), is added to the set \( E \). Note that \( r_i \) is also private information of buyer \( i \) in our model, so the auction network is defined according to reported \( r' = (r'_i)_{i \in N} \), where \( r'_i \) indicates the set of \( i \)'s followers to whom \( i \) forwards the information. To summarize, for each \( i \), the private information is given as \( \theta_i = (v_i, r_i) \), called the true type of \( i \), consisting of the true value \( v_i \) and the set \( r_i \) of the followers. Any reportable type \( \theta'_i = (v'_i, r'_i) \) of \( i \) with true type \( \theta_i = (v_i, r_i) \) satisfies \( r'_i \subseteq r_i \), i.e., a buyer can only forward the information to her followers. Let \( R(\theta_i) \) be the set of all reportable types by \( i \) with \( \theta_i \). Also, let \( \Theta \) denote the profile of types reported by all buyers and \( \Theta_r \) denote the set of all possible type profiles. For notation simplicity, we introduce additional technical terms regarding the auction network. A buyer \( i \) is connected if a path \( s \to \cdots \to i \) in \( G \) is formed based on the reported \( r' \). Let \( \mathcal{N} \) denote the set of connected buyers. For each \( i \), let \( d(i) \) denote the distance of the shortest path from \( s \) to \( i \). If \( i \) is not connected, we assume \( d(i) = \infty \). Given \( \theta' \), a buyer \( j \in \mathcal{N} \) is a critical parent of \( i \in \mathcal{N} \) if, without \( j \)'s participation, \( i \) is not connected, i.e., \( j \) appears in any path from \( s \) to \( i \) in \( G \). Let \( P_i(\theta') \subseteq \mathcal{N} \) denote the set of all critical parents of \( i \) under \( \theta' \). The buyer \( j \in P_i(\theta') \) closest to \( i \) is called the least critical parent of \( i \). An allocation \( x \) is feasible if \( \sum_{i \in N} x_i \leq k \), and \( x_i = 1 \) implies \( i \in \mathcal{N} \) for each \( i \in N \). Let \( \mathbf{X} \) be the set of all feasible allocations.

Now we are ready to give a formal description of (direct revelation) mechanisms. A mechanism \((f, t)\) consists of two components, an allocation rule \( f \) and a profile of transfer rules \((t_i)_{i \in N}\). An allocation rule \( f \) maps a profile \( \theta' \) of reported types to a feasible allocation \( f(\theta') \in \mathbf{X} \). We sometimes use the notation of \( f(\theta'_i, \theta''_i) \) instead, especially when we focus on the report of a specific buyer \( i \), where \( \theta'_i \) indicates the profile of types reported by the others. Given \( \theta'_i, f_i(\theta'_i) \in [0, 1] \) denotes the assignment to buyer \( i \). Each transfer rule \( t_i \) maps a profile \( \theta' \) to a real number \( t_i(\theta') \in \mathbb{R} \), which indicates the amount that buyer \( i \) pays to the seller.

Here, we define several properties that mechanisms should satisfy. Feasibility requires that for any input, the allocation returned by the mechanism is feasible.

**Definition 1.** A mechanism \((f, t)\) is feasible if for any \( \theta' \), \( f(\theta') \) is feasible.

Strategy-proofness is an incentive property, requiring that, for any buyer, reporting its true valuation and forwarding the information to all of its followers is a dominant strategy.

**Definition 2.** Given a mechanism \((f, t)\) and a buyer \( i \) with true type \( \theta_i = (v_i, r_i) \), a report \( \theta'_i = (v'_i, r'_i) \in R(\theta_i) \) is a dominant strategy if for any \( \theta''_i \) and \( \theta'_i \in R(\theta_i) \),

\[
 v_i \cdot f(\theta'_i, \theta''_i) - t_i(\theta'_i, \theta''_i) \geq v_i \cdot f(\theta'_i, \theta'_i) - t_i(\theta'_i, \theta'_i)
\]

holds. A mechanism \((f, t)\) is strategy-proof if reporting \( \theta_i \) is a dominant strategy for any \( i \) under \((f, t)\).

Individual rationality is a property related to the incentives of the buyers for participation, which requires that truth-telling guarantees a non-negative utility.

**Definition 3.** A mechanism \((f, t)\) is individually rational if for any \( i, \theta_i, \text{ and } \theta''_i \),

\[
 v_i \cdot f(\theta'_i, \theta''_i) - t_i(\theta'_i, \theta''_i) \geq 0
\]

holds.

Non-deficit is a property about seller’s revenue, which requires that the seller’s revenue cannot be negative. Note that it does not consider each individual transfer and thus does not imply the non-negativity of each buyer’s payment.

**Definition 4.** A mechanism \((f, t)\) satisfies non-deficit if for any \( \theta' \), \( \sum_{i \in N} t_i(\theta'_i) \geq 0 \) holds.

Non-wastefulness is a property about the efficiency of allocation, which requires that the mechanism allocate as many units as possible. Note that the traditional definition of non-wastefulness ignores the network structure, and thus the second term in RHS is replaced with \(|N|\).

\footnote{As discussed in the appendix, the revelation principle holds under our assumption \( R \) on reportable subset \( r'_i \subseteq r_i \). Therefore, focusing on direct revelation mechanisms is w.l.o.g.}
Definition 5. A mechanism \((f, t)\) is non-wasteful if for any \(\theta', \sum_{i \in N} f_i(\theta') \geq \min\{k, |N|\}\) holds.

2.1 Two Naïve Mechanisms for Comparison

One might expect that those properties hold in naïve mechanisms. Indeed, we can easily find the following two candidates. The formal definitions are in the appendix. We compare their performances with that of our new mechanism in the following sections.

The first mechanism applies VCG to only the direct buyers \(r_s\). It satisfies strategy-proofness, individual rationality, non-deficit, and non-wastefulness for \(|r_s| \geq k\). We refer to this mechanism as No-Diffusion-VCG (ND-VCG in short). Such a mechanism is also considered in Li et al. (2017), although they focused on single-item auctions.

The second mechanism gives the units to buyers for free, in the first-come-first-served manner, which is referred to as FCFS-F. It satisfies individual rationality, non-deficit, and non-wastefulness, and it is strategy-proof when earlier arrivals are not allowed, e.g., based on ascending order of \(d(\cdot)\), as usually assumed in online mechanism design (Hajiaghayi, Kleinberg, and Parkes 2004; Todo et al. 2012).

3 Distance-Based Mechanism

The definition of the new mechanism is given in Definition 6. A key concept in describing the mechanism is the diffusion critical tree \(T(\theta')\), originally introduced in Zhao et al. (2018). Given \(\theta'\), the diffusion critical tree \(T(\theta')\) is a rooted tree, where \(s\) is the root, the nodes of \(T(\theta')\) are all the connected buyers \(N\), and for each node \(i \in N\) and its least critical parent \(j \in P(\theta')\), an edge \((j, i)\) is drawn. If \(P(\theta') = \emptyset\), we draw an edge \((s, i)\). Furthermore, given \(T(\theta')\) and a node \(i\), all of the nodes in the subtree of \(T(\theta')\) rooted at \(i\) are called \(i\)'s descendants. Also, given a report \(\theta'\), a subset \(S \subseteq N\), and an integer \(k' \leq k\), \(v^*(S, k')\) denotes the \(k'\)th highest value in \(S\) under \(\theta'\). For \(k' \leq 0\), let \(v^*(S, k') = \infty\). In addition, if \(|S| < k'\), then \(v^*(S, k') = 0\).

Definition 6. Given \(\theta'\), first order the connected buyers \(N\) in ascending order of \(d(\cdot)\), with arbitrary fixed tie-breaking. Note that \(d(\cdot)\) is the distance from \(s\) in the original graph, not the distance in \(T(\theta')\). The order \(\triangleright\) is called the priority order. For each \(i \notin N\), \(d(\theta') = 0\). For each \(i \in N\), let \(N_i-1\) be the set of all connected buyers except \(i\) and its descendants in \(T(\theta')\). It then runs as follows:

1. \(k' \leftarrow k, W \leftarrow \emptyset\)
2. for each \(i \in N\) selected in the order of \(\triangleright\) do
3. \(p_i \leftarrow v^*(N_i-1 \setminus W, k')\)
4. if \(v'_i \geq p_i\) then
5. \(f_i(\theta') \leftarrow 1, t_i(\theta') \leftarrow p_i\)
6. \(k' \leftarrow k' - 1, W \leftarrow W \cup \{i\}\)
7. else
8. \(f_i(\theta') \leftarrow 0, t_i(\theta') \leftarrow 0\)
9. end if
10. end for

The following example demonstrates how the distance-based mechanism works. The network of buyers, defined by \(r\), as well as their true values, is shown in Fig. 1.

Example 1. Consider three units and seven buyers \(N = \{i_1, i_2, \ldots, i_7\}\). Each vertex in the left figure of Fig. 1 corresponds to a buyer, and the number in each vertex denotes her true valuation. The priority order is given as \(i_1 \succ i_2 \succ \cdots \succ i_7\). Assume that every buyer forwards the information to all of her followers, i.e., \(N = N\). The corresponding diffusion critical tree is given on the right in Fig. 1.

The assignment to buyers is computed one-by-one, in the priority order. For buyer \(i_1\), the price is given as \(p_{i_1} = v^*(N_{-i_1} \setminus W, k - |W|) = v^*\{i_2, i_3, i_4, i_5, i_6, i_7\}, 3\) = \(v_{i_2} = 50\). Since \(p_{i_1} > v_{i_2}\), she does not win a unit. For buyer \(i_2\), the price is given as \(p_{i_2} = v^*\{i_1, i_3, i_5, i_6, i_7\}, 3\) = \(v_{i_2} = 40\). Note that \(v_{i_2}\) is ignored because \(i_2\) is a critical parent of \(i_3\). Since \(v_{i_3} > p_{i_3}\), she wins a unit; \(W\) is updated to \(\{i_2\}\), and \(k\) is decremented to 2. For \(i_3\), the price is given as \(p_{i_3} = v^*\{i_1, i_4\}, 2\) = \(v_{i_3} = 30\). Since \(v_{i_3} > p_{i_3}\), she wins a unit; \(W\) is updated to \(\{i_2, i_3\}\), and \(k\) is decremented to 1. For \(i_4\), the price is given as \(p_{i_4} = v^*\{i_1, i_5, i_6, i_7\}, 1\) = \(v_{i_4} = 66\). Since \(p_{i_4} > v_{i_4}\), she does not win a unit.

For \(i_5\), the price is given as \(p_{i_5} = v^*\{i_1, i_4\}, 1\) = \(v_{i_5} = 45\). Since \(v_{i_5} > p_{i_5}\), she wins a unit; \(W\) is updated to \(\{i_2, i_3, i_5\}\) and \(k\) is decremented to 0. Since no unit remains, the prices for the remaining buyers, \(i_6\) and \(i_7\), become infinity, and thus neither of the buyers wins a unit. To sum up, \(i_2, i_3, i_5, i_6, i_7\) are winners, who pay 40, 30, and 45 respectively.

Let us clarify how it differs from GIDM by Zhao et al. (2018) and how it maintains strategy-proofness. GIDM first assigns, according to the reported \(\theta'\), a certain number of units to each subtree of \(T(\theta')\). The buyers in a subtree then compete with each other to buy the units assigned to it. This is something like creating a sub-market for each subtree. However, by not forwarding the information, some buyer, who originally loses due to the existence of some winner parent, can reduce the number of units assigned to the subtree, make the sub-market more competitive and the parent losing, and obtain a chance to win. This is actually the case found by Takanashi et al. (2019).

The distance-based mechanism also uses the diffusion critical tree. However, it does not create such a sub-market for each subtree. Instead, it has a single market with all of the units, where buyers’ priorities are defined based on the distance \(d(\cdot)\), which is not successfully manipulable; no buyer can make the distance shorter by not forwarding the infor-
mation to her followers, which is shown by Lemma 1.

3.1 Properties of Distance-Based Mechanism

We show feasibility, individual rationality, and non-deficit in Theorem 1, non-wastefulness in Theorem 2 and strategy-proofness in Theorem 3. The proofs of Theorems 1 and 2 are in the appendix. Let \( W \) denote a set of winners \( \{w_1, w_2, \ldots \} \) and \( W_{\sim j} \) denote \( \{w \in W \mid w \sim j\} \).

**Theorem 1.** The distance-based mechanism satisfies feasibility, individual rationality, and non-deficit.

**Theorem 2.** The distance-based mechanism is non-wasteful.

**Theorem 3.** The distance-based mechanism is strategy-proof.

**Proof.** Let \( (f, t) \) be the distance-based mechanism. It suffices to show that (I) a buyer has no incentive not to forward information to her followers, and that (II) a buyer cannot obtain any gain by misreporting her value. That is, for any \( \theta_i = (v_i, r_i) \) and \( \theta'_i = (v'_i, r'_i) \in R(\theta_i) \), consider an intermediate type \( \theta'^{m}_i = (v_i, r'_i) \). The strategy-proofness condition thus holds from (I) \( v_i \cdot f_i(\theta_i, \theta'_i) \geq v_i \cdot f_i(\theta_i, \theta''_i) \geq t_i(\theta_i, \theta''_i) \) and (II) \( v'_i \cdot f'_i(\theta'_i, \theta''_i) - t_i(\theta'_i, \theta''_i) \) holds. These inequalities are proven in Lemmas 1 and 2.

**Lemma 1.** For any \( i, \theta_i = (v_i, r_i), \theta'_{i-1}, \) and \( \theta'_i = (v'_i, r'_i) \) s.t. \( r'_i \subset r_i, v_i \cdot f_i(\theta_i, \theta'_{i-1}) - t_i(\theta_i, \theta'_{i-1}) \geq v_i \cdot f_i(\theta'_i, \theta'_{i-1}) - t_i(\theta'_i, \theta'_{i-1}) \).

**Proof.** By not forwarding the information, \( i \) can affect another buyer \( j \) in one of the following ways: (i) buyer \( j \), who is originally a descendant of \( i \) in \( T(\theta'_i) \), becomes disconnected, (ii) for buyer \( j \), which originally satisfies \( i \sim j \), the distance \( d(j) \) becomes larger. In case (i), \( j \) is originally not included in \( \hat{N}_{i-1} \). Furthermore, making \( j \) disconnected might decrease the price of other buyers \( j' \) s.t. \( j' \sim i \). There is a chance that \( i \)’s price increases. Thus, not forwarding the information is useless in case (i). In case (ii), even when \( d(j) \) becomes larger, \( i \sim j \) holds originally, and \( i \)’s price does not change. Thus, not forwarding the information is futile.

**Lemma 2.** For any \( i, \theta_i = (v_i, r_i), \theta'_{i-1}, \) and \( \theta'_i = (v'_i, r'_i) \), \( v_i \cdot f_i(\theta_i, \theta'_{i-1}) - t_i(\theta_i, \theta'_{i-1}) \geq v'_i \cdot f_i(\theta'_i, \theta'_{i-1}) - t_i(\theta'_i, \theta'_{i-1}) \).

**Proof.** For buyer \( i \), her price \( p_i \) is given as: \( v^*(\hat{N}_{i-1} \setminus W_{\sim i}, k - |W_{\sim i}|) \). It is clear that \( p_i \geq v^*(\hat{N}_{i-1}, k) \) holds. Let \( \tau_i \) denote \( v^*(\hat{N}_{i-1}, k) \). \( \tau_i \) is determined independently from \( i \)’s declared evaluation value. If \( v_i \leq \tau_i \) holds, \( i \) cannot gain a positive utility regardless of her declaration. Thus, assume \( v_i > \tau_i \) holds. Her actual price, i.e., \( p_i = v^*(\hat{N}_{i-1} \setminus W_{\sim i}, k - |W_{\sim i}|) \), can be strictly larger than \( \tau_i \). If some buyer \( j \) (where \( j \sim i \)) s.t. \( v_j' \leq \tau_i \) becomes a winner. Note that if \( v_j' > \tau_i \) holds, \( j \) is within the top \( k - 1 \) winners in \( \hat{N}_{i-1} \); the fact that \( j \) becomes a winner does not change \( p_i \).

The only way for \( i \) to decrease her price is to turn such a winner into a loser by over-bidding. Assume \( j \) (where \( j > i \)) is such a winner. If \( j \) is \( i \)’s ancestor, \( i \) cannot affect \( j \)’s price. Thus, \( j \) and \( i \) are in different branches in \( T(\theta') \). Since \( j \) is a winner, \( v_j' \geq v^*(\hat{N}_{j-1} \setminus W_{\sim j}, k - |W_{\sim j}|) \) holds. Also, to increase \( j \)’s price, \( v_i \) must be smaller than or equal to \( v^*(\hat{N}_{j-1} \setminus W_{\sim j}, k - |W_{\sim j}|) \). Note that \( i \) is included in \( \hat{N}_{j-1} \setminus W_{\sim j} \). If \( i \) is within the top \( k - |W_{\sim j}| - 1 \) buyers in \( \hat{N}_{j-1} \setminus W_{\sim j} \), even if \( i \) over-bids, she cannot change \( j \)’s price. Thus, \( v_j' \geq v_i \) holds. However, we assume \( v_j' < v_i \) holds. This is a contradiction. Thus, \( i \) cannot decrease her price by misreporting her evaluation value.

4 Efficiency Analysis

In this section we conduct a more detailed analysis on efficiency. We show that any winner has a value that is in the set of top-\( k \) buyers except for her descendants. Also, the social surplus of the distance-based mechanism is always as large as those of the two naive ones. Furthermore, the worst-case inefficiency of the distance-based mechanism can be bounded by choosing an appropriate reserve price.

4.1 Bounded Efficiency

Pareto efficiency in the multi-unit auction with \( k \) units requires that each buyer is a winner only if she is in the set of top-\( k \) buyers, i.e., whose value is more than or equal to the \( k \)-th highest value. However, it is not compatible with strategy-proofness in our model with the buyers’ network, since a buyer would have an incentive for not forwarding information to her descendants if she needs to compete with them. Thus, we introduce a weaker concept called bounded efficiency, which is consistent with the incentive of buyers to forward the information. We say an allocation satisfies bounded efficiency if each winner is in the set of top-\( k \) buyers except for its descendants. Also, a mechanism satisfies bounded efficiency if it always obtains a bounded efficient allocation. By ignoring the descendants of each buyer, the incentive of information forwarding can still be guaranteed.

Indeed, our mechanism satisfies bounded efficiency.

**Proposition 1.** The distance-based mechanism satisfies bounded efficiency: \( \forall i \in \hat{N} \text{ s.t. } f_i(\theta') = 1, \# \{j \in \hat{N}_{i-1} \mid v_j' > v_i'\} < k \).

**Proof.** Let \( i \in \hat{N} \) be an arbitrarily chosen winner and \( W \subset \hat{N} \setminus \{i\} \) be the set of winners chosen before \( i \) in the mechanism. By definition, the winner \( i \) faces the price \( v^*(\hat{N}_{i-1} \setminus W, k - |W|) \). Since \( i \) is a winner, \( v_i' \geq v^*(\hat{N}_{i-1} \setminus W, k - |W|) \) holds, implying that there are less than \( k - |W| \) buyers in \( \hat{N}_{i-1} \setminus W \), whose values are strictly larger than \( v_i' \), i.e., \( \# \{j \in \hat{N}_{i-1} \setminus W \mid v_j' > v_i'\} < k - |W| \). Therefore, regardless of how many winners in \( W \) have a strictly larger value than \( v_i' \), it holds that \( \# \{j \in \hat{N}_{i-1} \mid v_j' > v_i'\} < k \).
This property is useful to show other characteristics of our mechanism, e.g., Proposition 2. One can also easily observe that the two naïve mechanisms violate this property.

4.2 Social Surplus Domination

A mechanism \((f, p)\) is said to dominate another mechanism \((f', p')\) in terms of social surplus if for any \(N\) and any \(\theta'\), it holds that \(\sum_{i \in N} v_i \cdot f_i(\theta') \geq \sum_{i \in N} v_i \cdot f_i'(\theta')\).

Proposition 2. The distance-based mechanism dominates both ND-VCG and FCFS-F in terms of social surplus, but not vice versa.

Proof. When \(|N| \leq k\), every buyer receives a unit both in the distance-based mechanism and in ND-VCG. We then consider the cases of \(|N| > k\). First observe that, when \(v_s = \bar{v}\), i.e., there only exist the direct buyers, the set of winners in both mechanisms coincides, so that the top-\(k\) buyers win a unit; this is obvious from the definition for ND-VCG, and it also holds for the distance-based mechanism from Proposition 1.

Furthermore, when we add new buyers into the network one by one, in the ascending order of their distances from the source, an original winner becomes a loser in the distance-based mechanism only when her value is lower than the value of the new buyer who have just been added. Therefore, the arrival of a new buyer then weakly increases the social surplus, while it does not change that of ND-VCG. Also, there exists a case where the social surplus strictly increases. Thus, the distance-based mechanism dominates ND-VCG but not vice versa.

In the distance-based mechanism, each of the first \(k\) buyers, who is a winner in FCFS-F, loses only when there exists some buyer who arrives later and has a larger value. The distance-based mechanism therefore dominates FCFS-F, but not vice versa.

4.3 Worst-Case Efficiency Loss

When the seller wants to maximize revenue, it is natural to consider introducing a reserve price, i.e., the threshold bidding value for each buyer to own the right to win a unit (Myerson 1981). Letting \(v_h\) be the reserve price that the seller introduces, the distance-based mechanism with a reserve price \(v_h\) is then implemented by adding \(k\) dummy vertices with value \(v_h\), each of which is connected only to \(s\) (see Fig. 2), while in line 2 of the algorithm the dummies are not considered. In other words, those dummies only affect \(N_i\) for each \(i \in N\) and have no chance to win. The following example, which uses the same format of the reports with Example 1, demonstrates how the introduction of a reserve price changes the allocation.

Example 2. See Fig. 2. Since there are three units, the mechanism first adds three dummy vertices. The price for \(i_1\) is given as \(p_{i_1} = 50\), and she is not allocated a unit. The price for \(i_2\) is given as \(p_{i_2} = 45\), and she wins a unit. The price for \(i_3\) is given as \(p_{i_3} = 40\), which comes from the valuation of the dummy buyer. Since her value is strictly less than \(p_{i_3}\), she is not allocated a unit. The price for \(i_4\) is given as \(p_{i_4} = 50\), and she is not allocated a unit. The price for \(i_5\) is given as \(p_{i_5} = 40\), and she wins a unit. At this moment one unit remains. For buyer \(i_6\), the price is given as \(p_{i_6} = 45\), which is strictly less than her value of 66. Thus, she wins a unit.

Nearly identical proofs work for feasibility, non-deficit, individual rationality, and strategy-proofness. However, the introduction of a reserve price obviously breaks down non-wastefulness. Actually, for any non-zero \(v_h\), there is a case where no buyer wins a unit, e.g., \(v_i < v_h\) for every \(i \in N\). This implies that, when we consider the approximation ratio an efficiency measure, the distance-based mechanism with reserve price performs poorly. Even worse, the original definition without a reserve price still has an arbitrarily worse (i.e., arbitrarily close to zero) approximation ratio.

Nevertheless, it remains important to clarify the effect of different reserve prices, given the practical usefulness of reserve prices. We therefore consider the following worst case efficiency measure called \(\alpha\)-inefficiency, inspired by Nath and Sandholm (2018), and find that the optimal reserve price is \(\bar{v}/2\), where \(\bar{v}\) is the upper bound of the value, i.e., for each \(i \in N\), \(v_i \leq \bar{v}\).

Definition 7. Let \(\bar{v}\) be the upper bound of the value. A mechanism \((f, t)\) is \(\alpha\)-inefficient if

\[
\alpha = \frac{1}{k\bar{v}} \sup_{\theta' \in \Theta} \max_{x \in X} \left[ \sum_{i \in N} v'_i \cdot x_i - \sum_{i \in N} v'_i \cdot f_i(\theta') \right].
\]

The range of \(\alpha\) is \([0, 1]\), and having a smaller \(\alpha\) is better. We first provide a lemma that is useful to provide the worst-case inefficiency, while its proof appears in the appendix. Given \(\theta'\), let \(\ell\) denote the number of connected buyers whose values are less than \(v_h\), i.e., \(\ell := \#\{i \in \hat{N} \mid v_i \geq v_h\}\).

Lemma 3. Assuming all buyers declare their true values, \(\min(\ell, k)\) units are allocated in the distance-based mechanism with a reserve price.

Given the above lemma, we show that the distance-based mechanism with \(v_h = \bar{v}/2\) satisfies 1/2-inefficiency.

Theorem 4. The distance-based mechanism with reserve price \(v_h\) satisfies 1/2-inefficiency by setting \(v_h = \bar{v}/2\).

Proof. If \(\ell < k\), the distance-based mechanism allocates units to the top \(\ell\) buyers within \(\hat{N}\) (in terms of values) from Lemma 3. The remaining \(k - \ell\) units cannot be allocated.
since the values of other buyers are less than $v_h$. Thus, the maximum efficiency loss is bounded by $(k - \ell)v_h$ (if $k - \ell$ buyers exist whose values are $v_h - \epsilon$, the efficiency loss becomes $(k - \ell)(v_h - \epsilon)$). In particular, if the value of each buyer is less than $v_h$, $\ell$ becomes 0. Thus, the worst case efficiency loss is $k \cdot v_h$.

When there are $k$ units to the closest buyers closer to $k$-th unit, since the values of other buyers are less than $\bar{v}$, the performance by the mechanism with a reserve price, where the mechanism achieves remains an open question. However, since 0-inefficiency implies Pareto efficiency, the impossibility suggested by Takashashi et al. (2019) implies that no strategy-proof mechanism that also satisfies non-deficit and individual rationality achieves 0-inefficiency.

5 Revenue Analysis

The seller’s revenue is also an important evaluation criterion for auction mechanisms. In this section, we first show that the seller’s revenue in the distance-based mechanism is no less than those of the two naive ones. We also show that maximizing the revenue by optimally choosing the set of its followers to whom it sends the information is NP-complete.

5.1 Revenue Domination

We define the domination in terms of the seller’s revenue analogously. A mechanism $(f, p)$ dominates another mechanism $(f', p')$ in terms of the seller’s revenue if for any $N$ and any $\theta'$, it holds that $\sum_{i \in N} t_i(\theta') \geq \sum_{i \in N} t_i(\theta)$.

**Proposition 3.** The distance-based mechanism dominates both ND-VCG and FCFS-F in terms of the seller’s revenue, but not vice versa.

**Proof.** The distance-based mechanism obviously dominates ND-VCG when $|r_s| \leq k$, since the price for each winner in ND-VCG is zero. When $|r_s| > k$, each winner in ND-VCG pays $v^*(r_s \setminus \{i\}, k)$. On the other hand, the price $p_i$ for each winner $i$ in the distance-based mechanism satisfies $p_i \geq v^*(N_{i-1}, k)$ by definition. For every winner $i$, $N_{i-1}$ is a superset of $r_s \setminus \{i\}$. Therefore, from the monotonicity of $v^*$ on the first argument, $p_i \geq v^*(N_{i-1}, k) \geq v^*(r_s \setminus \{i\}, k)$ holds. Also, there exists a case where the inequality becomes strict. Thus, the distance-based mechanism dominates ND-VCG but not vice versa. Since the revenue of FCFS-F is always zero, while the revenue of the distance-based mechanism is non-negative for any input and can be strictly positive, the distance-based mechanism also dominates FCFS-F but not vice versa.

5.2 Revenue Monotonicity

The seller’s revenue is required to have some specific form of monotonicity. Several forms of such revenue monotonicity have been studied, including bidder revenue monotonicity (Rastegari, Condon, and Leyton-Brown 2011) [Todo, Iwasaki, and Yokoo 2010] and item revenue monotonicity, a.k.a. destruction-proofness (Muto and Shirata 2017).

The condition studied in this section is weaker than bidder revenue monotonicity. A mechanism is follower revenue monotonic if the seller’s revenue is monotonically increasing with respect to the number of direct buyers. Let $t_i(\theta^| r_s')$ be the payment from buyer $i$ when $\theta^*$ is reported and $s$ sends the information of the auction to a subset $r_s'$ of direct buyers.

**Definition 8.** A mechanism $(f, t)$ is follower revenue monotonic if for any $r_s$, $\theta^*$, and $r_s' \subseteq r_s$, it holds that $\sum_{i \in N} t_i(\theta^| r_s') \geq \sum_{i \in N} t_i(\theta^| r_s')$.

For a multi-unit auction without any network among buyers, there are several bidder revenue monotonic mechanisms, and thus follower revenue monotonic ones. However, the example below shows that, for auction via social network, our mechanism is not even follower revenue monotonic.

**Example 3.** Consider two units and four buyers $i_1$, $i_2$, $i_3$, and $i_4$; see Fig. 3. The priority order is $i_1 > i_2 > i_3 > i_4$.

Assume all of the buyers behave sincerely. When the seller $s$ sends the information to all of its followers, i.e., $i_1$, $i_2$, and $i_3$, all buyers become connected. The price for each buyer is given as $p_1 = 6$, $p_2 = 6$, $p_3 = 15$, and $p_4 = 6$, where $i_2$ and $i_4$ win a unit and the revenue is 12. When $s$ sends the information only to $i_1$ and $i_2$, $i_3$ becomes unconnected. The price for each buyer is given as $p_1 = 6$, $p_2 = 15$, and $p_4 = \infty$, where $i_1$ and $i_2$ win a unit and the revenue is 15. As a result, the revenue is not maximized when the seller sends the information to all the direct buyers.

Therefore, a question rises to the seller: to which set of direct buyers should she send the information to maximize her revenue? We define a simplified form of this problem, so called OPTIMAL DIFFUSION, from the perspective of computational complexity: Assuming that the seller knows the exact network among buyers and that all buyers behave sincerely, she tries to find an optimal set of direct buyers to whom she should send the information.

**Definition 9 (OPTIMAL DIFFUSION).** Given a number $k$ of units, a profile $\theta^*$, a set $r_s$ of direct buyers, and a threshold $K$, is there a subset $r_s' \subseteq r_s$ s.t. $\sum_{i \in N} t_i(\theta^| r_s') \geq K$ holds under the distance-based mechanism?
We show that \textsc{Optimal Diffusion} is NP-complete by a reduction from \textsc{Partition}. Due to space limitations, we present a proof sketch below; a full proof is in the appendix.

\textbf{Definition 10 (\textsc{Partition}).} \textit{Given a set \( A \) where each \( i \in A \) has a value \( v(i) \in 2^\mathbb{R} \), does there exist a subset \( A' \subseteq A \) such that \( \sum_{i \in A'} v(i) = m \), where \( m = \sum_{i \in A} v(i) / 2^2 \)?}

\textbf{Theorem 5.} \textsc{Optimal Diffusion} is NP-complete.

\textit{Proof Sketch.} First, \textsc{Optimal Diffusion} is in NP since we can compute \( \sum_{i \in \mathcal{N}} t_i(\theta) | r'_s \) in polynomial time. Given an instance of \textsc{Partition}, we construct an instance of \textsc{Optimal Diffusion} as follows, with \( \mathcal{N} = \mathcal{N}^A \cup \mathcal{N}^B \cup \mathcal{N}^C \):

1. For all \( i \in \mathcal{A} \), we create set \( (a^i_0)_{0 \leq j \leq v(i)} \) in \( \mathcal{N}^A \) such that \( \theta_{a^i_0} = (\epsilon, (a^i_j)_{1 \leq j \leq v(i)}) \), and \( \theta_{a^i_j} = (v(i), 0) \) for \( 1 \leq j \leq v(i) \).
2. Set \( \mathcal{N}^B = (b_j)_{1 \leq j \leq m+2} \) is such that \( \theta_{b_1} = (v_3, \{b_2\}) \), \( \theta_{b_2} = (v_3, \{b_3\}) \) for \( 2 \leq j \leq m+1 \), and \( \theta_{b_m+2} = (v_4, 0) \).
3. Set \( \mathcal{N}^C = (c_j)_{1 \leq j \leq m+1} \) is such that \( \theta_{c_j} = (\epsilon, \{c_{j+1}\}) \) for \( 1 \leq j \leq m \), and \( \theta_{c_m+1} = (v_5, 0) \).
4. The seller’s direct followers are \((a^0_i)_{i \in \mathcal{A}} \cup \{b_1, c_1\}\).

The network is illustrated in Fig. 4. Buyers are labelled with any ascending order of \( d(\cdot) \) satisfying \( b_{m+1} \succ c_m \). The prices satisfy \( \epsilon < v_3 < v_4 < v_5 \), and the number of units is \( k = m + 2 \).

We briefly argue the validity of the reduction. Notice that buyers \( b_1 \) and \( c_1 \) belong to any \( r'_s \subseteq r_s \) such that \( \sum_{i \in \mathcal{N}} t_i(\theta) | r'_s \geq K \), since otherwise price \( v_4 \) cannot be reached.

If \( \{a \in r'_s \mid v_a = v_1\} = m \) holds, i.e., exactly \( m \) descendants with value \( v_1 \) can be chosen (thus the original \textsc{Partition} is “yes”), then buyer \( b_1 \) buys at price \( \epsilon \), buyers \( (b_i)_{2 \leq i \leq m+1} \) at price \( v_1 \), and buyer \( c_m+1 \) at price \( v_4 \). Hence, \( \sum_{i \in \mathcal{N}} t_i(\theta) | r'_s = \epsilon + m \cdot v_1 + v_4 = K \) and \textsc{Optimal Diffusion} is “yes”.

If the original \textsc{Partition} is “no”, either (i) \( \{a \in r'_s \mid v_a = v_1\} < m \) or (ii) \( \{a \in r'_s \mid v_a = v_1\} > m \) holds. In the case (i), buyers \( b_1 \) and \( b_2 \) buy at price \( \epsilon \), hence, \( \sum_{i \in \mathcal{N}} t_i(\theta) | r'_s < K \) and \textsc{Optimal Diffusion} is “no”.

In the case (ii), buyer \( b_1 \) does not buy, and \( c_{m+1} \) buys at price lower than \( v_4 \). Hence, \( \sum_{i \in \mathcal{N}} t_i(\theta) | r'_s < K \) and \textsc{Optimal Diffusion} is “no”.

\section{Incentive Analysis}

Now we show that, compared with those two naïve mechanisms, our mechanism also has its own strength on buyers’ incentive; in those mechanisms, hiding the information, combined with the report of the true value, is also a dominant strategy, while this is not the case in our mechanism for any \( k \geq 2 \). This indicates that the incentive for each buyer to report her true value in the distance-based mechanism is stronger than that in both of those naïve ones.

\textbf{Proposition 4.} Assume \( k \geq 2 \). For each \( i \), reporting \((v_i, \emptyset)\) is not a dominant strategy in the distance-based mechanism.

\textit{Proof.} Consider \( k \) units and \( k + 2 \) buyers \( i_1, \ldots, i_{k+2} \), such that \( r_s = \{i_1, i_3, i_5, i_6, \ldots, i_{k+2}\} \), \( \theta_{i_1} = (15, \{i_2\}) \), \( \theta_{i_2} = (20, 0) \), \( \theta_{i_3} = (10, \{i_4\}) \), \( \theta_{i_4} = (9, 0) \), and \( \theta_{i_5} = (30, 0) \) for all \( 5 \leq j \leq k + 2 \). The priority is given as \( i_5 \succ i_6 \succ \cdots \succ i_{k+2} \succ i_3 \succ i_1 \succ i_4 \succ i_2 \). The first \( k - 2 \) units are sold to \( \{i_3\}_{5 \leq j \leq k+2} \), regardless of \( i_1 \)’s forwarding strategy. Under \( i_1 \)’s sincere forwarding to \( i_2 \), \( i_1 \) wins a unit and pays \( 9 \). If \( i_1 \) does not forward the information to \( i_2 \), then \( i_1 \) would win a unit and pay \( 10 \). So not forwarding the information is dominated by a sincere forwarding in this case.

\textbf{Proposition 5.} For each \( i \), reporting \((v_i, \emptyset)\) is a dominant strategy in both ND-VCG and FCFS-F.

\textit{Proof.} In ND-VCG, only the reports from the direct buyers affect the outcome. Therefore, for each direct buyer \( i \in r_s \), any valuation report \( v'_i \), and any action by other buyers, the choice of \( r'_i \subseteq r_i \) does not change the outcome at all.

In FCFS-F, for each \( i \in \mathcal{N} \), any follower of \( i \) who originally arrives after \( i \) under \( i \)’s sincere forwarding \( r_i \) is still arriving after \( i \) under any manipulation \( r'_i \subseteq r_i \). Thus, whether \( i \) wins a unit does not depend on the choice of \( r'_i \).

\section{Conclusions}

The distance-based mechanism satisfies strategy-proofness, non-wastefulness, non-deficit, and individual rationality. The performance is comprehensively analyzed; it dominates the two naïve mechanisms in terms of both social surplus and revenue. Several other properties are also revealed.

A more detailed analysis on the complexity of maximizing the seller’s revenue is required, such as for the case with a fixed number \( k \) of units. Our future work will also include more general revenue analysis, e.g., revenue equivalence (Hedénreit et al. 2009) and revenue optimality (Myerson 1981). Extending the distance-based mechanism to more general domains, such as multi-unit auctions with decreasing marginal values, is also crucial. Considering an obviously strategy-proof auction via social network will also be an interesting direction (Li 2017).
8 Acknowledgments

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A Discussion on Revelation Principle

The revelation principle is a fundamental concept of mechanism design, which specifies the relationship between direct revelation and indirect mechanisms. If an indirect mechanism has a dominant strategy equilibrium, then we can find a strategy-proof direct revelation mechanism that results in the same outcome in the equilibrium. However, in a non-standard setting, e.g., online mechanism design (Parkes 2007), the revelation principle might fail. Thus, we need to exert caution.

First, a direct revelation mechanism should not utilize any information that is unavailable in an indirect mechanism. On one hand, in our setting, the seller does not know the existence of the buyers who are not directly connected to her. On the other hand, in a direct revelation mechanism, we assume the mechanism designer knows $N$, i.e., all the buyers, and gets reports from each buyer in $N$. We require that in a feasible allocation, a direct revelation mechanism can only allocate a unit to a connected buyer. Thus, a feasible direct revelation mechanism does not utilize any information that is unavailable in an indirect mechanism.

Second, the space of possible manipulations in a direct revelation mechanism must be equivalent to that in an indirect mechanism. In our setting, a buyer can strategically stop forwarding the information to her followers. By assuming that buyer $i$, whose true followers are $r_i$, can report only $v'_i \leq r_i$, we preserve the equivalence. However, just preserving the equivalence is inadequate. An intuitive explanation why the revelation principle holds is as follows. Assume an indirect mechanism with a dominant strategy equilibrium. Then we can create a direct revelation mechanism, by introducing a mediator between the indirect mechanism and a participant. The mediator asks for the participant’s true type and plays her dominant strategy. So she does not have an incentive for lying to the mediator. When the possible manipulations/reportable types are restricted, this is no longer true. Intuitively, assume a participant misreports her type to the mediator. Then the mediator does the best manipulation based on the reported type. As a result, the space of possible manipulations in the direct revelation mechanism can be expanded more compared to that of the indirect mechanism.

Green and Laffont (1986) proposed a condition on reportable types called the nested range condition (NRC) and showed that it is actually a necessary and sufficient condition for the revelation principle to hold for the case of mechanism design with transfer functions, such as auctions. Intuitively, NRC is a transitivity condition, which requires that if an agent (buyer) with type $\theta_i$ can pretend to have type $\theta'_i$ and if an agent with type $\theta'_i$ can pretend to have type $\theta''_i$, then the agent with type $\theta_i$ can also pretend to have type $\theta''_i$. In our model, NRC obviously holds, since the restriction on $r_i$ satisfies transitivity, and there is no restriction on reportable valuation functions. Therefore, to discuss the outcome in a dominant strategy equilibrium in an auction via social network, focusing on direct revelation mechanisms is without loss of generality.

B The Formal Definitions of Two Naïve Mechanisms

Definition 11 (ND-VCG). Given $\theta'$, No-Diffusion-VCG $(f, t)$ is defined as follows:

$$f_i(\theta') = \begin{cases} 1 & \text{if } i \in r_s \land v'_i \geq v^*(r_s \setminus \{i\}, k) \\ 0 & \text{otherwise.} \end{cases}$$

$$t_i(\theta') = \begin{cases} v^*(r_s \setminus \{i\}, k) & \text{if } f_i(\theta') = 1 \\ 0 & \text{otherwise.} \end{cases}$$

Definition 12 (FCFS-F). Given $\theta'$, first label the connected buyers $\tilde{N}$ in an ascending order of $d(\cdot)$, as we did in the proposed mechanism (described in Definition 6). Assume w.l.o.g. that the order is $1, 2, \ldots, |\tilde{N}|$. Then, FCFS-for-Free $(f, t)$ is defined as follows:

$$f_i(\theta') = \begin{cases} 1 & \text{if } i \leq k \\ 0 & \text{otherwise.} \end{cases}$$

$$t_i(\theta') = 0 \text{ for all } i \in N$$

C Omitted Proofs for Section 3

Proof of Theorem 1. Let $(f, t)$ be the proposed mechanism.

Feasibility: Since $v^*(\cdot, k') = \infty$ for any $k' \leq 0$, and $k'$ is initialized by $k$ and decremented whenever a unit is sold (see lines 4–6 of the procedure), at most $k$ connected buyers buy a unit, i.e., $\sum_{i \in N} f_i(\theta') \leq k$ for any $\theta'$. Furthermore, since any unconnected buyer has no chance to buy a unit, feasibility is guaranteed.

Individual Rationality: Each buyer $i$ faces a price $p_i$ and buys a unit only when $v'_i \geq p_i$. Thus, under truth-telling, each buyer’s price is not strictly larger than the true value $v_i$ if she wins a unit, i.e., $v_i \geq p_i$, which guarantees individual rationality.

Non-Deficit: Furthermore, by the definition of $v^*$, the price for each winner is non-negative. Since each loser receives no compensation, it also satisfies non-deficit.

Proof of Theorem 2. Let $(f, t)$ be the distance-based mechanism. Consider an arbitrary report profile $\theta'$. If $|\tilde{N}| \leq k$, the price that each buyer $i \in \tilde{N}$ faces is $v^*(\tilde{N}_i \setminus W_{>i}, k - |W_{>i}|)$. Since $|\tilde{N}_i \setminus W_{>i}| < |\tilde{N}_i| - |W_{>i}| \leq k - |W_{>i}|$, the price is 0. Thus, the number of winners is $|\tilde{N}_i| = \min(k, |\tilde{N}_i|)$, satisfying non-wastefulness. We then focus on the case of $k < |\tilde{N}_i|$. Assume for the sake of contradiction that the number of units sold under $\theta'$ is strictly smaller than $k$. More specifically, let $m := \sum_{i \in N} f_i(\theta')$, we assume that $m < k$ holds.

Assume w.l.o.g. that the top $m + 1$ buyers among $\tilde{N}_i$ in terms of reported values, are labeled as $i_1, i_2, \ldots, i_{m+1}$ in a descending order of reported value $v'$, with an arbitrary tie-breaking, i.e., $v'_{i_1} \geq v'_{i_2} \geq \ldots \geq v'_{i_{m+1}}$. Also let $M$ be the top $m$ buyers, i.e., $M := \{i_1, \ldots, i_m\}$. First, we show by induction that each member of $M$ must be a winner. For the base case, let us show that $i_1$ obtains a unit. The price of $i_1$ is given as $v^*(\tilde{N}_{i_1} \setminus W_{>i_1}, k - |W_{>i_1}|)$. Since $k - |W_{>i_1}| \geq 1$
(note that we assume the number of winners is fewer than $k$), this value is less than or equal to $v^*(N_{-i_1}, 1) \leq v^*_{t_i}$. Thus, $i_1$ is a winner. For the inductive case, let us assume $M' = \{i_1, \ldots, i_k\}$ are winners. We show that $i_{k+1}$ is also a winner. Let $M''$ denote $\{i \in M' \mid d(i) < d(i_{k+1})\}$. Also, let $g_1$ denote $|M''|$ and $g_2$ denote $g - g_1$. Since $i_{k+1}$ is the $g + 1$-st buyer and $M'$ is the top set of $g$ buyers, $v^*_{t_{i_{k+1}}} = v^*(N \setminus W'', 1 + g - w')$ holds for any subset $W'' \subseteq M'$, where $w' := |W''|$. Furthermore, since the function $v^*$ is monotonic non-decreasing on the first argument, $\hat{N} \supseteq \hat{N}_{-i_{k+1}}$ implies $v^*(N \setminus W', 1 + g - w') \geq v^*(N_{-i_{k+1}} \setminus W', 1 + g - w')$. The price of $i_{k+1}$ is given as $v^*(N_{-i_{k+1}} \setminus W_{r_{i_{k+1}}} \setminus |W_{r_{i_{k+1}}} + 1|)$. Since $k - |W_{r_{i_{k+1}}} + 1| \geq g_2 + 1$ and $W_{r_{i_{k+1}}} + 1$ is a superset of $M''$, the price is smaller than or equal to $v^*(N_{-i_{k+1}} \setminus M'', g_2 + 1)$. Combining with the above inequality (where we choose $W''$ to $M''$, s.t. $|M''| = g_1$ and $g_2 = g - g_1$), the price is smaller than or equal to $v^*(N \setminus W', 1 + m - w') \geq v^*(N_{-i_{k+1}} \setminus W', 1 + m - w')$. The price that the buyer faces is given as $v^*(N_{-i_{k+1}} \setminus W_{r_{i_{k+1}}} \setminus k - |W_{r_{i_{k+1}}} + 1|))$. Since $m < k$ and both $m$ and $k$ are integers, $m + 1 \leq k$. Thus, we have $v^*(N_{-i_{k+1}} \setminus W_{r_{i_{k+1}}} + 1 + m - |W_{r_{i_{k+1}}} + 1|) \geq v^*(N_{-i_{k+1}} \setminus W_{r_{i_{k+1}}} + 1, k - |W_{r_{i_{k+1}}} + 1|)$ from the definition of $v^*$. Since $W_{r_{i_{k+1}}} + 1$ is a subset of $M$, from the above inequalities, we finally have $v^*_{t_{i_{k+1}}} \geq v^*(N_{-i_{k+1}} \setminus W_{r_{i_{k+1}}} + 1, k - |W_{r_{i_{k+1}}} + 1|)$, where RHS is the price that $i_{k+1}$ faces. Therefore, she also wins a unit, violating the assumption that only $m$ units are sold.

**D Omitted Proof for Section 4**

**Proof of Lemma 3.** If $\ell \geq k$, $k$ units are allocated from Theorem 2. Assume $\ell < k$. Let $M = \{i_1, \ldots, i_{\ell}\}$ denote the set of buyers whose evaluation values are more than or equal to $v^*$. Without loss of generality, we assume $v_{i_1} \geq v_{i_2} \geq \ldots \geq v_{i_{\ell}}$, and show that $i_{\ell}$ obtains a unit. For the base case, we show that $i_1$ obtains a unit. The price of $i_1$ is given as $v^*(N_{-i_1} \setminus W_{r_{i_1}} + k - |W_{r_{i_1}} + 1|)$. Since $k - |W_{r_{i_1}} + 1| \geq 1$, this value is less than or equal to $v^*(N_{-i_1}, 1) \leq v_{i_1}$. Thus, $i_1$ is a winner.

For the inductive case, assume $M' = \{i_1, \ldots, i_{\ell}\}$ are winners for any $g < \ell$. We show that $i_{\ell}$ is also a winner. Let $M''$ denote $\{i \in M' \mid d(i) < d(i_{\ell})\}$. Also, let $g_1$ denote $|M''|$ and $g_2$ denote $g - g_1$. Since $i_{\ell}$ is the $g + 1$-st buyer and $M'$ is the top set of $g$ buyers, it holds that $v^*_{t_{i_{\ell}}} = v^*(N \setminus W', 1 + g - w')$,

for any subset $W' \subseteq M'$, where $w' := |W'|$. Furthermore, since the function $v^*$ is monotonic non-decreasing on the first argument, $\hat{N} \supseteq \hat{N}_{-i_{\ell}}$ implies $v^*(N \setminus W', 1 + g - w') \geq v^*(N_{-i_{\ell}} \setminus W', 1 + g - w')$. The price of $i_{\ell}$ is given as $v^*(N_{-i_{\ell}} \setminus W_{r_{i_{\ell}}} + k - |W_{r_{i_{\ell}}} + 1|)$. Since $k - |W_{r_{i_{\ell}}} + 1| \geq g_2 + 1$ and $W_{r_{i_{\ell}}} + 1$ is a superset of $M''$, the price is smaller than or equal to $v^*(N_{-i_{\ell}} \setminus M'', g_2 + 1)$. Combining with the above inequality (where we choose $W''$ to $M''$, s.t. $|M''| = g_1$ and $g_2 = g - g_1$), we can see that the price is smaller than or equal to $v^*(N \setminus M'', 1 + g - |M''|)$, which equals $v^*_{t_{i_{\ell}}}$. Thus, $i_{\ell}$ must be a winner. Therefore, all the $\ell$ buyers are allocated a unit.

**E Omitted Proof for Section 5**

**Proof of Theorem 5.** First, OPTIMAL DIFFUSION is in NP since it is polynomial to compute $\sum_{i \in N} t_i(\theta'_i \mid r'_i)$. We show that this problem is NP-complete by a reduction from PARTITION. Given an instance of PARTITION, we construct an instance of OPTIMAL DIFFUSION as follows. First, let us partition the set of buyers in three subsets $N = N^A \cup N^B \cup N^C$.

- For each $i \in A$, we create $(v(i) + 1)$ buyers $(a_j)_{j \in [0, \ldots, v(i)]}$ in $N^A$ such that:
  - $\theta'_{a_0} = (\epsilon, (a_j)_{j \in [1, \ldots, v(i)]})$,
  - $\theta'_{a_1} = (v_1, \emptyset)$ for all $j \in [1, \ldots, v(i)]$.

- Set $N^B = (b_j)_{j \in [1, \ldots, m + 1]}$ is composed of $(m + 1)$ buyers such that:
  - $\theta'_{b_0} = (v_2, (b_2))$,
  - $\theta'_{b_j} = (v_3, (b_{j + 1}))$ for all $j \in [2, \ldots, m + 1]$,
  - $\theta'_{b_{m + 2}} = (v_4, \emptyset)$.

- Set $N^C = (c_j)_{j \in [1, \ldots, m + 1]}$ is composed of $(m + 1)$ buyers such that:
  - $\theta'_{c_0} = (\epsilon, (c_{j + 1}))$ for all $j \in [1, \ldots, m]$,
  - $\theta'_{c_{m + 1}} = (v_5, \emptyset)$.

The network construction is illustrated in Figure 5

The prices satisfy the following condition:

$$\epsilon < v_2 < v_1 < v_3 \ll v_4 < v_5$$

Buyers are labelled with any ascending order of $d(\cdot)$ satisfying that buyer $b_{m+1}$ has priority over buyer $c_{m+1}$. Finally, the number of unit is $k = m + 2$ and the threshold value is $K = \epsilon + m \cdot v_1 + v_4$.

Now, we show that there exists a set $A' \subseteq A$ such that $\sum_{a_j \in A'} v(i) + 1$ and only if there exists a set $r'_s \subseteq r'_s$ such that $\sum_{i \in N} t_i(\theta'_i \mid r'_s) \geq \epsilon + m \cdot v_1 + v_4$.

($\Rightarrow$) Assume that there exists a subset $A' \subseteq A$ such that $\sum_{i \in A'} v(i) + 1$. Consider the set $r'_s = \{a_{0_0} \in r'_s : i \in A' \} \cup \{b_1 \} \cup \{c_{1}\}$. Notice that when the seller shares the information with $r'_s$, the number of buyers with value $v_1$ involved in the auction is exactly $m$. Then the mechanism runs as follows:
Therefore, the revenue is \(\varepsilon + m \cdot v_1 + v_4\).

(\(\Leftarrow\)) Assume that there exists \(r_s' \subseteq r_s\) such that \(\sum_{i \in N} t_i(\theta' | r_s') \geq \varepsilon + m \cdot v_1 + v_4\). Since \(v_3 \ll v_4\) holds, the threshold value can only be attained when buyer \(c_{m+1}\) buys an unit at price \(v_3\). Since there exists only one buyer with value \(v_4\) (buyer \(b_{m+2}\)), it implies that \(b_1\) and \(c_1\) belong to \(r_s'\), and that there is only one unit left when the mechanism reaches buyer \(c_{m+1}\). Let us denote \#\(v_1\) the number of buyers with value \(v_1\) that are followers of buyers in \(r_s'\). Note that, independently from the value taken by \#\(v_1\), the buyers \((a_i^0)_{i \in A}\) always receive price \(v_3\) and thus they never buy. There are three cases to consider.

First, assume that \#\(v_1\) > \(m\), then the mechanism runs as follows:

- For buyer \(b_1\), there are \((m+1)\) values that are greater than \(v_2\) (one value \(v_5\) from buyer \(c_{m+1}\) and \(m\) values \(v_1\) from buyers \((a_i^1)_{a_i^0 \in r_s', j \in [1, \ldots, v_i]}\)). Hence, buyer \(b_1\) receives price \(\varepsilon\) and buys one unit.
- Buyer \(c_1\) receives price \(v_1\) and does not buy.
- Buyers \((a_j^1)_{a_i^0 \in r_s', j \in [1, \ldots, v_i]}\) receive price \(v_3\) and do not buy.
- For \(j \in [2, \ldots, m]\):
  - Buyer \(b_j\) receives price \(v_1\) and buys one unit.
  - Buyer \(c_j\) receives price \(v_3\) and does not buy.
- For \(j = m+1\), there are two units remaining, and thus buyer \(b_{m+1}\) receives price \(v_1\) and buys an unit. Then, buyer \(c_{m+1}\) receives price \(v_4\) and buys an unit. Finally, there is no unit left for buyer \(b_{m+2}\).

Hence the revenue is \((m+2) \cdot v_1\), which is a contradiction.

Now, assume that \#\(v_1\) < \(m\), then the mechanism runs as follows:
• For buyer $b_1$, there are at most $m$ values that are greater than $v_2$ (one value $v_5$ from buyer $c_{m+1}$ and at most $m - 1$ values $v_1$). Hence, buyer $b_1$ receives price $\epsilon$ and buys an unit.

• Buyer $c_1$ receives price $v_3$ and does not buy.

• Buyers $(a_j)_{i \in r'_s, j \in [1, \ldots, v(i)]}$ receive price $v_3$ and do not buy.

• For $j \in [2, \ldots, m]$:
  - Buyer $b_j$ receives price
    \[
    \begin{cases}
      \epsilon, & \text{if } j \leq m - \#v + 1, \\
      v_1, & \text{if } j > m - \#v + 1.
    \end{cases}
    \]
    and buys one unit.
  - Buyer $c_j$ receives price $v_3$ and does not buy.

• For $j = m + 1$, there are two units remaining. Buyer $b_{m+1}$ and then buyer $c_{m+1}$ receives price
  \[
  \begin{cases}
    \epsilon, & \text{if } \#v = 0, \\
    v_1, & \text{if } \#v \geq 1.
  \end{cases}
  \]
  and buys one unit each. Finally, there is no unit left for buyer $b_{m+2}$.

Hence the revenue is

\[
\begin{cases}
  \epsilon + (m - \#v_1) \cdot \epsilon + (\#v_1 + 1) \cdot v_1 & \text{if } \#v \neq 0, \\
  (m + 2) \cdot \epsilon & \text{if } \#v = 0.
\end{cases}
\]

Thus, it is strictly lower than $K$, which is a contradiction.

Finally, assume that $\#v_1 = m$, then the mechanism runs as it is described in the argument for $(\Rightarrow)$, and the revenue is thus $\epsilon + m \cdot v_1 + v_4$.

Therefore, in $r'_s$ and their followers, there exists exactly $m$ buyers with value $v_1$. Hence the set $A' = \{i \in A : a_0 \in r'_s\}$ is such that $\sum_{i \in A'} v(i) = m$. \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null \null
