A System for Distributed Mechanisms: Design, Implementation and Applications

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Abstract

We describe here a structured system for distributed mechanism design appropriate for the Internet applications. In our approach the players dynamically form a network in which they know neither their neighbours nor the size of the network and interact to jointly take decisions. The only assumption concerning the underlying communication layer is that for each pair of processes there is a path of neighbours connecting them. This allows us to deal with arbitrary network topologies.

We also discuss the implementation of this system which consists of a sequence of layers. The lower layers deal with the operations relevant for distributed computing only, while the upper layers are concerned only with communication among players, including broadcasting and multicasting, and distributed decision making. This yields a highly flexible distributed system whose specific applications are realized as instances of its top layer. This design is implemented in Java.

The system supports fault-tolerance and can be augmented by a provision for distributed policing the purpose of which is to exclude 'dishonest' players. Also, it can be used for repeated creation of dynamically formed networks of players interested in a joint decision making implemented by means of a tax-based mechanism. We illustrate its flexibility by discussing a number of implemented examples.

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1 Introduction

1.1 Background and motivation

Mechanism design is one of the important areas of economics. To quote from [7], it deals with the problem of 'how to arrange our economic interactions so that, when everyone behaves in a self-interested manner, the result is something we all like.' So these interactions are supposed to yield desired social decisions when each agent is interested in maximizing only his own utility.

The traditional approaches rely on the existence of a central authority who collects the information from the players, computes the decision and informs the players about the outcome and their taxes. The increasing reliance on decision making carried out through Internet leads to a natural need for distributed solutions that do not rely on any central authority. But how to translate such real-world considerations into design and implementation that can be used in practice?

This question was recently addressed in a series of papers distributed mechanism design. In this setting no central authority exists and the decisions are taken by the players themselves. The challenge here is to appropriately combine the techniques of distributed computing with those that deal with the matters specific to mechanism design, notably rationality (i.e., appropriately defined self-interest) and truth-telling (i.e., incentive compatibility).

However, to properly implement decision making in the context of the Internet one needs to address other issues, as well. First of all, one should provide an *open system* that can deal with the initially unknown number of interested users. Second, one should support *connectivity* between the users who can dynamically join the system. Further, one should be able to cope with unreliable (hacked or faulty software or hardware in) user devices that can lead to system failures. Also, it is desirable to provide ways of dealing with the dishonest users, such as their identification and possible exclusion. These additional issues have been hardly considered in the papers of distributed mechanism design. In this paper we discuss a system for distributed mechanism design that addresses all these issues and that can be readily used in the Internet setting.

1.2 Related work

A number of recent papers deal with different aspects of distributed computing in connection with game theory and mechanism design.

Among them, some focus on complexity such as communication complexity. Some target computation/communication/incentive compatibility and eventually faithful implementation. Others try to build a secure computation in a distributed system. More recently, there has been a series of work on distributed constraint optimization and partial centralized techniques.

The authors of [12] focused on message communication by players in a distributed game. However, they assume that there is a center to which every player is directly connected. An influential paper [6] introduced the notion of distributed algorithmic mechanism design emphasizing the issues of computational complexity and incentive compatibility in distributed computing. Next, [13] studied the distributed implementations of the VCG mechanism. However, in their approach there is still a center that is ultimately responsible for selecting and enforcing the outcome.

The authors of [18] considered the problem of creating distributed system specifications that will be faithfully implemented in networks with rational (i.e., self-interested) nodes so that no node will choose to deviate from the specification. They used interdomain routing as an example and suggested ways to detect when nodes deviate from their specified communication. In turn, [8] proposed in the context of secure computation a stronger form of computation in that it solely depends on players' rationality instead of their honesty.

Researchers of [16] introduced the first distributed implementation of the VCG mechanism. The only central authority required was a bank that is in charge of the computation of taxes. The authors also discussed a method to redistribute some of the VCG payments back to players. Finally, [15] proposed a new partial centralization technique, PC-DPOP, based on the DPOP algorithm of [14]. PC-DPOP provides a better control over what parts of the problem are centralized and allows this centralization to be optimal with respect to the chosen communication structure.

1.3 Contributions

In this paper we propose a platform for distributed mechanism design that can be readily used in the context of the Internet and customized to specific purposes. Also it can be used for a repeated distributed decision making process, each round involving a different group of interested players.

Our platform supports the distributed implementation of the large class of tax-based mechanisms that implement the decisions either in dominant strategies or in a Nash equilibrium (see, e.g., [10]). This aspect of our work is closest to [16] whose approach is based on distributed constraint programming. In contrast, our approach builds upon a very general view of distributed programming, an area that developed a variety of techniques appropriate for the problem at hand and that is more appropriate for the Internet applications.

To support the Internet-based applications we ensure connectivity between the players by means of a ***backbone*** of interconnected ***local registries***. The dynamic network creation is realized by means of players' ***registration*** in their local registries. This allows us to support the open system aspect of the platform by allowing the presence of initially unknown number of interested players.

To realize concrete applications we only need to provide a backbone of local registries and select specific registration schemes for participating in the mechanism. The former can be taken care of by stipulating that each geographic or logical region, such as a country, city, or Internet domain has its own local registry. Interested players can find the addresses of their respective local registries in public fora, e.g., local government web sites. To take care of the latter we can for example stipulate that the registration is successful only if it took place before a certain deadline that refers to a global clock, or if some quorum (minimum number) of registered players is reached at each local registry, and/or if a global quorum of registered players is reached.

Our platform is built out of a number of layers. This leads to a flexible, hierarchical design in which the lower layers are concerned only with the matters relevant for distributed computing, such as communication and synchronization issues, and are clearly separated from the upper layers that deal with the relevant aspects of the mechanism design, such as computation of the desired decision.

More specifically, the lowest communication layer allows us to detect process failure and provides an asynchronous, non-order-preserving `send` operation. The next layer provides a message efficient, fault-tolerant distributed termination detection (see, e.g., [11]) algorithm. In turn, the high-level communication layer supports a generic ***broadcast command*** that supports communication among players and ensures that each broadcast message is eventually delivered to each registered player. Its implementation relies only on the assumption that for each pair of registered players there is a path of neighbouring processes connecting them. Any specific application, such as an appropriate instance of the Groves mechanism (see, e.g., [10]), is realized simply as an *instantiation of a top layer*. Finally, the deliberately limited GUI prevents players from tampering with the system.

This layered architecture, in conjunction with the use of local registries and registration requirement, offers a number of novel features and improvements to the approach of [16], to wit

- we deal with a larger class of mechanisms, notably Groves mechanisms. They include the VCG mechanism and various forms of redistributions of VCG payments recently studied in the literature (and considered in [16]). Additionally, we can easily tailor our platform to other tax-based mechanisms, such as Walker mechanism (see [19]),
- we support open systems in which the number of players can be unknown,
- the bank process of [16] is replaced by a weaker ***tax collector*** process. It is needed only for the mechanisms that are not balanced, wherein it is a passive process used only to receive messages to collect the resulting deficit,
- ***fault-tolerance*** is supported, both on the message transmission level and on the player processes level (with an option for a *restart* in the case of the detection of a failed player process),
- a multi-level protection against ***manipulations*** is provided,
- our platform makes it possible to implement ***distributed policing*** that provides an alternative to a 'central enforcer' whose responsibility is to implement the outcome decided by the agents and collect the taxes (see, e.g., [5, page 366]).

Fault-tolerance at the mechanism design level means that the final decision and taxes can be computed even after some of the processes that broadcast the players' types crash: the other processes then still can proceed. This is achieved by the duplication of the computation by all players. Such a redundancy is common in all approaches to fault-tolerance (and also used to prevent manipulations, see [5, page 366]). In [17] it is used to realize two natural requirements for a distributed mechanism implementation: computation compatibility and communication compatibility. Redundancy was intentionally avoided in [16] which aimed at minimizing the overall communication and computation costs. In our approach it allows the fastest process to 'dominate' the computation and move it forward more quickly.

This design is implemented in Java and was tested on a number of examples including Vickrey auction with redistribution, two types of auctions and a sequential mechanism design, described in the second part of the paper.

1.4 Paper organization

In the next section we review the basic facts about the tax-based mechanisms, notably the Groves family of mechanisms. Then in Section 3 we discuss the issues that need to be taken care of when moving from the centralized tax-based mechanisms to distributed ones and what approach we took to tackle these issues. The details of our design and implementation are provided in Section 4.

Next, in Section 5, we discuss three important advantages of our design: security, distributed policing and fault-tolerance. The aim of Section 6 is to present a number of examples of mechanisms that we implemented using our system. Then, in Section 7 we provide conclusions and discuss future work. Finally, in two appendices we discuss the details of our algorithm that computes the tax scheme and present a sample interaction with our system.

2 Mechanism design: the classical view

We recall here briefly tax-based mechanisms, notably the family of Groves mechanisms, see, e.g., [10, Chapter 23]. Assume a set of ***decisions*** D, a set $\{1, \ldots, n\}$ of players, for each player a set of ***types*** Θ_i and a ***utility function*** $v_i : D \times \Theta_i \rightarrow \mathcal{R}$. In this context a type is some private information known only to the player, for example a vector of player's valuations of the items for sale in a multi-unit auction.

A ***decision rule*** is a function $f : \Theta \rightarrow D$, where $\Theta := \Theta_1 \times \cdots \times \Theta_n$. We call the tuple

$$(D, \Theta_1, \ldots, \Theta_n, v_1, \ldots, v_n, f)$$

a ***decision problem***.

A decision rule f is called ***efficient*** if for all $\theta \in \Theta$ and $d' \in D$

$$\sum_{i=1}^{n} v_i(f(\theta), \theta_i) \geq \sum_{i=1}^{n} v_i(d', \theta_i),$$

and ***strategy-proof*** (or ***incentive compatible***) if for all $\theta \in \Theta$, $i \in \{1, \ldots, n\}$ and $\theta'_i \in \Theta_i$

$$v_i(f(\theta_i, \theta_{-i}), \theta_i) \geq v_i(f(\theta'_i, \theta_{-i}), \theta_i),$$

where $\theta_{-i} := (\theta_1, \ldots, \theta_{i-1}, \theta_{i+1}, \ldots, \theta_n)$ and $(\theta'_i, \theta_{-i}) := (\theta_1, \ldots, \theta_{i-1}, \theta'_i, \theta_{i+1}, \ldots, \theta_n)$.

In mechanism design one is interested in the ways of inducing the players to announce their true types, i.e., in transforming the decision rules to the ones that are strategy-proof. In ***tax-based*** mechanisms this is achieved by extending the original decision rule by means of ***taxes*** that are computed by the central authority from the vector of the received types, using players' utility functions.

Given a decision problem, in the classical setting, one considers then the following sequence of events, where f is a given, publicly known, decision rule:

(i) each player i receives a type θ_i,

(ii) each player i announces to *the central authority* a type θ'_i; this yields a joint type $\theta' := (\theta'_1, \ldots, \theta'_n)$,

(iii) the central authority then makes the decision $d := f(\theta')$, computes the sequence of taxes $t := g(\theta')$, where $g : \Theta \to \mathcal{R}^n$ is a given function, and communicates to each player i the decision d and the tax $|t_i|$ he needs to pay to (if $t_i \leq 0$) or to receive from (if $t_i > 0$) the central authority.

(iv) the resulting utility for player i is then $u_i(d, t) := v_i(d, \theta_i) + t_i$.

Each ***Groves mechanism*** is obtained using $g(\theta') := (t_1(\theta'), \ldots, t_n(\theta'))$, where for all $i \in \{1, \ldots, n\}$

- $h_i : \Theta_{-i} \to \mathbb{R}$ is an arbitrary function,
- $t_i : \Theta \to \mathbb{R}$ is defined by

$$t_i(\theta') := h_i(\theta'_{-i}) + \sum_{\substack{j=1 \\ j \neq i}}^{n} v_j(f(\theta'), \theta'_j).$$

Intuitively, the sum $\sum_{j \neq i} v_j(f(\theta'), \theta'_j)$ represents the society benefit from the decision $f(\theta')$, with player i excluded.

The importance of the Groves mechanisms is revealed by the following crucial result, in which we refer to the expanded decision rule $(f, g) : \Theta \to D \times \mathcal{R}^n$.

Groves Theorem Suppose the decision rule f is efficient. Then in each Groves mechanism the decision rule (f, g) is strategy-proof w.r.t. the utility functions $u_1, \ldots, u_n$.

The proof is remarkably straightforward so we reproduce it for the convenience of the reader.

Proof. Since f is efficient, for all $\theta \in \Theta$, $i \in \{1, \ldots, n\}$ and $\theta'_i \in \Theta_i$ we have

$$\begin{aligned} u_i((f,t)(\theta_i, \theta_{-i}), \theta_i) &= \sum_{j=1}^{n} v_i(f(\theta_i, \theta_{-i}), \theta_i) + h_i(\theta_{-i}) \\ &\geq \sum_{j=1}^{n} v_i(f(\theta'_i, \theta_{-i}), \theta_i) + h_i(\theta_{-i}) \\ &= u_i((f,t)(\theta'_i, \theta_{-i}), \theta_i). \end{aligned}$$

$\Box$

When for a given tax-based mechanism for all θ' we have $\sum_{i=1}^{n} t_i(\theta') \leq 0$, the mechanism is called ***feasible*** (which means that it can be realized without external financing) and when for all θ' we have $\sum_{i=1}^{n} t_i(\theta') = 0$, the mechanism is called ***balanced*** (which means that it can be realized without a deficit).

Each Groves mechanism depends on the functions $h_1, \ldots, h_n$. A special case, called ***Clarke mechanism***, or ***Vickrey-Clarke-Groves mechanism*** (in short ***VCG***) is obtained by using

$$h_i(\theta'_{-i}) := -\max_{d \in D} \sum_{j \neq i} v_j(d, \theta'_j).$$

So then

$$t_i(\theta') := \sum_{j \neq i} v_j(f(\theta'), \theta'_j) - \max_{d \in D} \sum_{j \neq i} v_j(d, \theta'_j).$$

Hence for all θ' and $i \in \{1, \ldots, n\}$ we have $t_i(\theta') \leq 0$, which means that the VCG mechanism is feasible and that each player needs to make the payment $|t_i(\theta')|$ to the central authority. Other feasible Groves mechanisms exist in which some players receive the payments and others have to make the payments, for example the one proposed in [4], which we discuss in Subsection 6.1.

3 Our approach

In our approach we relax a number of the assumptions made when introducing mechanism design. More specifically we assume that

- there is no central authority,
- players interested in participating in a specific mechanism register to join an open system wherein that mechanism runs. A tax collector process is part of this system,
- the players whose registration is accepted inform other registered players about their types,
- once a registered player learns that he has received the types from all registered players, he computes the decision and the taxes, sends this information to other registered players, and possibly the tax collector process, and terminates his computation.

We also assume that there is no collusion among the players. This leads to an implementation of the mechanism design by means of anonymous (i.e., name independent) distributed processes, in absence of any central authority. Because of the distributed nature of this approach no global state, in particular no global clock, exists. The computation of the decision and of the taxes is carried out by the players themselves.

As it stands, this revised setting is not clear on a number of counts. First, we need to clarify the registration process, in particular what it implies and when it ends. In our approach each player is represented by a process, in short a ***player process***. A player who wishes to join a specific mechanism (e.g., an auction) must register with a ***local registry***. Local registries are linked together in a network that satisfies the full reachability condition described in Subsection 4.2 (and we assume one of them is designated as the initiator mentioned in that subsection). Receiving his registration request, a local registry verifies the eligibility of a player (e.g., whether his IP address puts him under the jurisdiction of this registry) and accepts his request if the registration conditions for the specific mechanism (e.g., a deadline) are met.

Second, once the registration process ends, in the resulting network a player process may not know the identities of other player processes, so the announcement of one's type to all other players needs to be explained. In our approach we assume that once a player process is registered, it joins the network of (registry and player) processes wherein a generic ***broadcast*** command is available. The implementation of this command relies only on the assumption that for each pair of players there is a path of neighbouring processes connecting them. This allows us to deal with arbitrary network topologies in a simple way.

The topology of this network is irrelevant both from the point of view of the individual processes, as well as the semantics of the broadcast command. The full reachability of the backbone network of local registries is enough to ensure that as long as each player process knows and is known by its local registry, full reachability also holds for the whole network. The broadcast command uses the connectivity of this network to ensure that a copy of a broadcast message is eventually delivered to every registered player in finite time. These messages are transmitted through paths managed in a lower layer which the player processes *cannot access*.

This automatically prevents manipulation by player processes of messages originating from or destined for other players. Such manipulations are possible in other schemes, such as in [5, page 366], where the player processes connected in a ring are computing a Vickrey (second-price) auction of a single good. The processes are expected to pass around a message containing the top two bids for that good. This opens the possibility of cheating by a process by simply manipulating the messages that it is expected to pass through. Indeed, by putting a high bid and by substantially lowering the second lowest bid a player process can get the good more cheaply (at least when it is the last player process to bid). In our set up a player process cannot access the bids of other player processes before broadcasting its own bid (unless one explicitly considers a sequential set up, see Subsection 6.4). Moreover, no messages destined for a player process pass through another player process.

Third, we need to clarify how each player process will know that he indeed received the types announced by *all other* registered players. We solve this problem by assuming that each player process after broadcasting the player's type participates in a ***distributed termination detection algorithm*** the aim of which is to learn whether all players have indeed broadcast their types. This algorithm is tailored to deal with the communication by means of multicasting (which subsumes broadcasting).

If this algorithm detects termination, the player process knows that he indeed received all types, and in particular can determine at this stage the number of players and their names. From that moment on each player process uses the same naming scheme when referring to other player processes. The uniqueness is ensured by a local scheme for generating globally unique player identifiers. More generally, we use the distributed termination detection algorithm to delineate the end of each *phase* of the distributed computation: registration, type broadcast, etc., i.e., for ***barrier synchronization*** (see, e.g., [1]).

Fourth, to ensure the correctness of the above approach, it is crucial that each player process computes the same decision and the same information concerning taxes. The former is taken care of by the fact that each player process uses the same, publicly known, decision rule f that each player learns, for example from a public bulletin board, and that is used by the player process after its registration is accepted.

Further, each player process applies f to the same input θ' and computes *the same* ***tax scheme*** by which we mean a specific vector of payments $tax(t_1), \ldots tax(t_n)$ computed from the tax vector $(t_1, \ldots, t_n)$, where $tax(t_j)$ specifies the amounts that player j has to pay to other players and possibly the tax collector from his tax t_j. All tax schemes $tax(t_1), \ldots tax(t_n)$ then determine 'who pays how much to whom'. In general most taxes equal 0, so we optimize the computation by generating ***reduced tax schemes*** in which only non-zero entries are listed and by multicasting them instead of broadcasting. Note also that to compute the taxes each player process needs to know the utility functions of other player processes. The tax collector process is only needed for the mechanisms that are not balanced.

Finally, it is important to note that our approach allows for a ***repeated mechanism***, that is several rounds of decision making can take place, by means of the same given mechanism, each time involving a possibly different group of players. To this end we need to logically separate each round of the mechanism. This is handled, again, using our distributed termination detection algorithm for barrier synchronization.

4 Implementation

Our distributed mechanism design system is implemented in Java. The implementation follows the guidelines explained in the previous section. Figure 1 shows the overall architecture of our system and the different layers of software used in its implementation. The implementation of the first two layers is about 9K lines of Java code. It was developed by Kees Blom and took about 2 man years. The remainder of the system is about 3.5K lines of Java code and was developed by Huiye Ma during the last 9 months. We also relied on software for message passing between internet-based parallel processes developed by Han Noot. Each entity in this architecture communicates, either through function calls or method invocations, *only* with its adjacent entities. Specific applications are realized by instantiating the crucial player process layer.

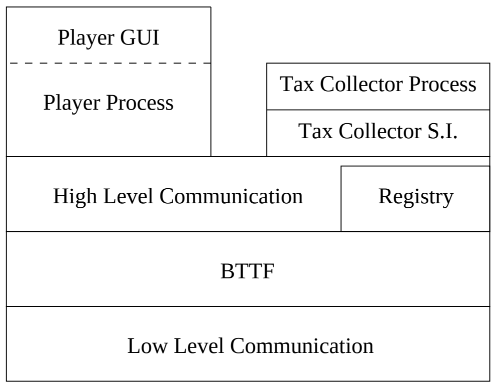

Figure 1: Implementation architecture

4.1 Low Level Communication

The Low Level Communication (LLC) layer supports (1) locally generated, globally unique process identifiers, and (2) reliable non-order-preserving, asynchronous, targeted communication, exclusively through the exchange of passive messages between processes. The only means of communication between processes in LLC is through message passing, where no transfer of control takes place when messages are exchanged.

Targeted means that the sender of a message explicitly specifies the recipient of the message. *Asynchronous* means that the receiver of a message is not guaranteed to have received the message upon the completion of the send operation. *Non-order-preserving* means that the temporal order of messages sent from the same sender to the same receiver is not necessarily preserved. *Reliable* means that every message sent by a sender will be received by its target receiver in finite but indeterminate time, without alteration and in its entirety (unless the receiver process fails or terminates). A message sent to a non-existent (terminated or failed) process will be returned to its sender intact, in finite but indeterminate time (a time-out).

The interface provided by the LLC layer contains the two operations `llsend(m, r)` and `llreceive(m, t)`. The `llsend(m, r)` operation sends the message `m` to its target process `r` and returns a Boolean value that indicates the success or failure of the operation. A send operation may fail, for instance, if the size of the message is above the capacity threshold of the transport mechanism, or due to other possible internal errors. Successful send simply means that the message has been dispatched on its way to its specified target.

The `llreceive(m, t)` operation blocks its calling process, p, until either (a) a message sent to p has arrived, or (b) the specified time-out `t` has expired. In the first case, `llreceive()` returns `true` and passes the received message in `m`. In the second case, this function returns `false` to indicate that the time-out `t` has expired.

4.2 BTTF

The Back To The Future (BTTF) layer implements a message efficient, fault-tolerant distributed termination detection (DTD) algorithm, on top of the LLC layer. The details of the BTTF DTD algorithm are described in [3] and lie beyond the scope of this paper. We describe here only those salient features of this algorithm and its implementation that are pertinent for our application.

Specifically, the BTTF layer contains the implementation of the BTTF Wave algorithm, which is a wave DTD algorithm. All wave DTD algorithms determine termination using a cascading wave of special control messages, called tokens. They also require the designation of a single process as the ***initiator***, which is responsible for initiating the token waves, and typically, several rounds of token waves are necessary for the initiator to detect global termination. In each round, a cascading wave of tokens travels through every process in the system and collects its status information for the initiator.

In the BTTF algorithm, the initiator is anonymous, i.e., no process (other than the initiator) knows who the initiator is. All aspects of token handling and termination detection are transparently handled internally by the BTTF algorithm. The BTTF Wave algorithm is message efficient: in the absence of process failures, to detect termination in a system of m processes that exchange a total of n normal messages, it requires only $O(n)$ control messages plus 2 rounds of token waves, where each round contains between $O(m)$ to $O(m^2)$ token messages. The BTTF algorithm transparently detects and tolerates persistent process failures through an optional probing mechanism. Probing adds an extra cost of $O(n)$ control messages. Termination detection is costlier when process failures actually occur, because they may increase the number of required rounds of token waves: the BTTF Wave algorithm requires 2 successive failure-free rounds to detect termination.

Every process in the BTTF Wave algorithm must maintain a set of identifiers of $k \geq 0$ other processes in the system, called its *buddies*. The buddies sets of processes are transparently used by the BTTF Wave algorithm to cascade its token waves. The processes in the buddies set of a process p may or may not be the same as (some of) the processes that communicate with (i.e., send messages to, or receive messages from) p. The only requirement on the buddies sets of processes is that they must collectively provide the initiator with full reachability.

More precisely, let P be the finite set of processes in a system, and let $b^1(p)$ designate the buddies set of a process $p \in P$. For integers $i > 0$, define

$$b^{i+1}(p) = \bigcup_{x \in b^i(p)} b^i(x) \ \cup \ b^i(p).$$

Since P is finite, there exists an $i > 0$ for which the above definition reaches a fixed point $b^*(p)$, where $b^*(p) = b^{i+1}(p) = b^i(p)$. The full reachability requirement of the BTTF algorithm holds if for the initiator process $a \in P$, $b^*(a) \ \cup \ \{a\} = P$. Even when the failure of a process $x \in P$ partitions the remaining processes $P \setminus \{x\}$ into two or more mutually unreachable subsets, the BTTF algorithm continues undeterred in the partition $b^*(a) \ \cup \ \{a\} \setminus \{x\} \subset P \setminus \{x\}$ that includes the initiator process a. (In the calculation of $b^*(a)$, the $b^1(x)$ of a failed process x is $\emptyset$.)

In practice, there are many simple, local schemes that guarantee the full reachability requirement of the BTTF algorithm. For instance, in the common case where a system starts from a single process which transitively creates all other processes in the system, it is sufficient that each process keeps only its immediate parent and its immediate children in its buddies set. In this case, any process can be designated as the initiator, and each round of token waves involves $O(m)$ token messages.

Aside from its responsibility to maintain its buddies list (e.g., adding its newly created children processes), a process using the BTTF algorithm is oblivious to the details of termination detection and failure recovery. A process starts by calling the initialization function provided by the BTTF layer. At this point the process is *active*. While active, a process can use the send and receive functions of the BTTF to send and receive messages to and from other processes. A process becomes *passive* when it is prepared to terminate. Termination is detected when all processes in the system are passive. It is possible for a process that is (still) active to send a message to a passive process, which when received, will automatically change the status of the receiver back to active, allowing it to send and receive more messages.

The BTTF layer provides two receive functions in its interface: `receive()` and `passiveReceive()`. A process uses `receive()` when it expects to receive a message from another process, while it is *not* prepared to terminate. A call to `receive()` blocks until it returns either with a received message, or when its optionally specified time-out parameter expires. Calling `passiveReceive()` indicates that the process is prepared to terminate, unless it receives a message. A call to `passiveReceive()` blocks until it returns either with a received message, or with an indication that global termination has been detected.

The DTD functionality provided by the BTTF layer can be used for barrier synchronization as well as for termination detection. Once `passiveReceive()` indicates termination has been detected, the calling process knows that all processes in the system have reached the same 'termination barrier'. This termination barrier is either the actual termination of the processes, or the virtual termination of only the current phase of the activity in the system. In the first case, the calling process must perform its local clean-up and terminate. In the second case, the process must start a new *phase* of its computation by calling the initialization function of the BTTF layer once more.

The implementation of the BTTF layer requires only the `llsend(m, r)` and `llreceive(m, t)` operations provided by the LLC layer. It provides an interface consisting of the following functions:

- `initializeBTTFWave(...)` This function (re)initializes the calling process, enabling it to participate in the (next phase of) global computation. The details of the parameters of this function are beyond the scope of this paper.

- `insertBuddy(p)` This function call inserts the specified process `p` in the buddies set of the calling process.

- `removeBuddy(p)` This function call removes the specified process `p` from the buddies set of the calling process.

- `send(m, T)` This function implements a delayed multicast operation. It schedules a copy of the message `m` to be sent to every process in the target set of processes `T`. The actual dispatch of the messages to their specified targets will take place upon a subsequent call to one of the functions `prioritySend()`, `receive()`, or `passiveReceive()`.

- `prioritySend(m, T)` This function implements a multicast operation. It first sends all messages scheduled by earlier calls to `send()`, if any, and then sends a copy of the message `m` to every process in the target set of processes `T`.

- `receive(m, t)` The parameter `t` is an integer value. Negative `t` values indicate indefinite wait, and non-negative values specify a time-out value in milliseconds. A call to this function blocks until either the specified time-out expires, or a message sent to the calling process is available. If the specified time-out expires, the return result of this function is `false` and the value of `m` is undefined. If a received message is available, this function returns the message in `m` and returns `true`.

- `passiveReceive(m)` A call to this function blocks until either global termination (of the current phase of the computation) is detected, or a message sent to the calling process is available. If termination is detected, the return result of this function is `false` and the value of `m` is undefined. If a received message is available, this function returns the message in `m` and returns `true`.

4.3 High Level Communication and Registry

The High Level Communication (HLC) layer provides indirect, anonymous communication among the players in a distributed system. It includes a number of local registries whose mutual connectivity supports the full connectivity of the players necessary for broadcast. A player must sign-in at a local registry, after which it can use the other operations provided by the HLC layer to take part in the mechanism. It provides the following functions:

- `signin(r, mech)` This function allows the calling player process to sign at the local registry `r` so that it can take part in the mechanism `mech`. The player can start the first phase of the mechanism `mech` right after a successful return of a call to this function.

- `signout(mech)` This function terminates the participation of the calling player process in the mechanism `mech`.

- `bsend(m)` This function broadcasts the message `m` to all registered players in the game.

- `msend(m, T)` This function multicasts the message `m` to every player in the target set `T`.

- `receive(m, t)` This function is the same as its homonym in the BTTF layer.

- `passiveReceive(m)` This function is the same as its homonym in the BTTF layer.

Each local registry is responsible for processing the registrations of the player processes according to the assumed registration criteria. Also, it maintains for each implemented mechanism the corresponding ***locking policy***. Each such policy regulates the conditions under which the player processes can receive messages sent to them or can broadcast or multicast messages. It is loaded each time a player process successfully registers. We shall return to this matter in the next subsection and in Subsection 6.4.

4.4 Player Process

Specific applications are implemented using this top layer. It is built on top of the HLC layer and is used to implement specific actions of the players, in particular the computation of the decisions and taxes. In our implementation of the distributed mechanism design the following sequence of actions takes place for each player i, where `flag` is a local Boolean variable. By `termination loop` we mean here the statement

```
while (passiveReceive(m)) {
  process message m;
}
```

and by `inspect loop` we mean the statement

```
flag = false;
while (receive(m, 100)) {
  if (m is the pair (decision, tax scheme)) {
    flag = true;
    process message m;
  }
}
```

where 100 is some arbitrary time-out in miliseconds.

The details of the processing of each received message `m` depend on the context.

(i) process p_i representing player i is created and assigned a globally unique name,

(ii) p_i obtains player i's type,

(iii) p_i signs in at the local registry `r` in its region using the `signin(r, mech)` call,

(iv) if p_i receives the confirmation of the registration (the call of `signin(r, mech)` is successful), it broadcasts player i's type using the `bsend()` function (and otherwise it terminates),

(v) p_i performs the `termination loop`. The corresponding `process m` statement in this loop consists of storing the type received from another registered player process. When this loops ends (that is, when p_i has received the types from all registered player processes and the global termination is detected) p_i has a globally unique naming scheme at its disposal to refer to the registered player processes, and the number of registered players n that equals the number of types it has received,

(vi) p_i performs the `inspect loop` to determine whether another process has already computed the decision and the tax scheme. If this is the case, `flag` will be set `true`,

(vii) if `flag` is not `true`, p_i computes the decision and the tax scheme of the players and multicasts using the `msend()` function the decision and the tax scheme to the processes representing players who need to pay or receive taxes and the decision to the other processes. If p_i needs to pay some tax $t' > 0$ to the tax collector, it sends this information to the tax collector process using the `msend()` function,

(viii) p_i performs the `termination loop`,

(ix) when it ends and after p_i receives from the tax collector process the total amount of taxes the tax collector received, p_i performs the `termination loop` again and terminates.

The details of the tax scheme algorithm can be found in Appendix I. The above description of the player process assumes that the underlying mechanism is *simultaneous*. The corresponding locking policy, loaded by the local registry, blocks the `receive(m, t)` and `passiveReceive(m)` functions of the p_i process until it has broadcast its type.

4.5 Tax Collector Software Interface

This layer is built on top of the HLC layer. It provides two functions also available in the HLC layer, `passiveReceive(m)` and `bsend(m)`, and two new functions, `tsignin(r, mech)` and `tsignout(mech)`, which are the counterparts of the `signin(r, mech)` and `signout(mech)` functions of the HLC layer and which are used to deal with the tax collector process registration.

4.6 Tax Collector Process

This layer is built on top of the Tax Collector Software Interface layer and is used to implement the actions of the tax collector which is in charge of collecting players' taxes. The following sequence of actions takes place for it:

(i) The tax collector process *ta* representing the tax collector is created and assigned a globally unique name known to every player. It signs in at the local registry in his region using the `tsignin(r, mech)` call (which always succeeds),

(ii) *ta* performs the `termination loop` (to synchronize the computation phases with the player processes),

(iii) *ta* performs the `termination loop` again. When it ends, the tax collector process has received all the taxes from the players. They are kept on a single account,

(iv) *ta* broadcasts the total amount on its single account to all players,

(v) *ta* performs the `termination loop` and terminates.

4.7 Player GUI

The interaction between the player (user) and the system is realized in this interface. The interaction is limited to the registration, type submission and tax reception.

5 Security, Distributed Policing and Fault-tolerance

Let us discuss now some consequences of this design.

5.1 Security

The architecture presented in the previous section allows multiple alternative implementations, in each of which the constituents that comprise each layer get allocated to run on a different set of hosts. Figure 2 shows an example mapping of constituents to 'logical hosts'. In any concrete implementation one or more such logical hosts can represent the same actual physical host.

At the core of Figure 2 lies a ***communications network***, represented by the cloud shape, that interconnects a number of hosts to provide the

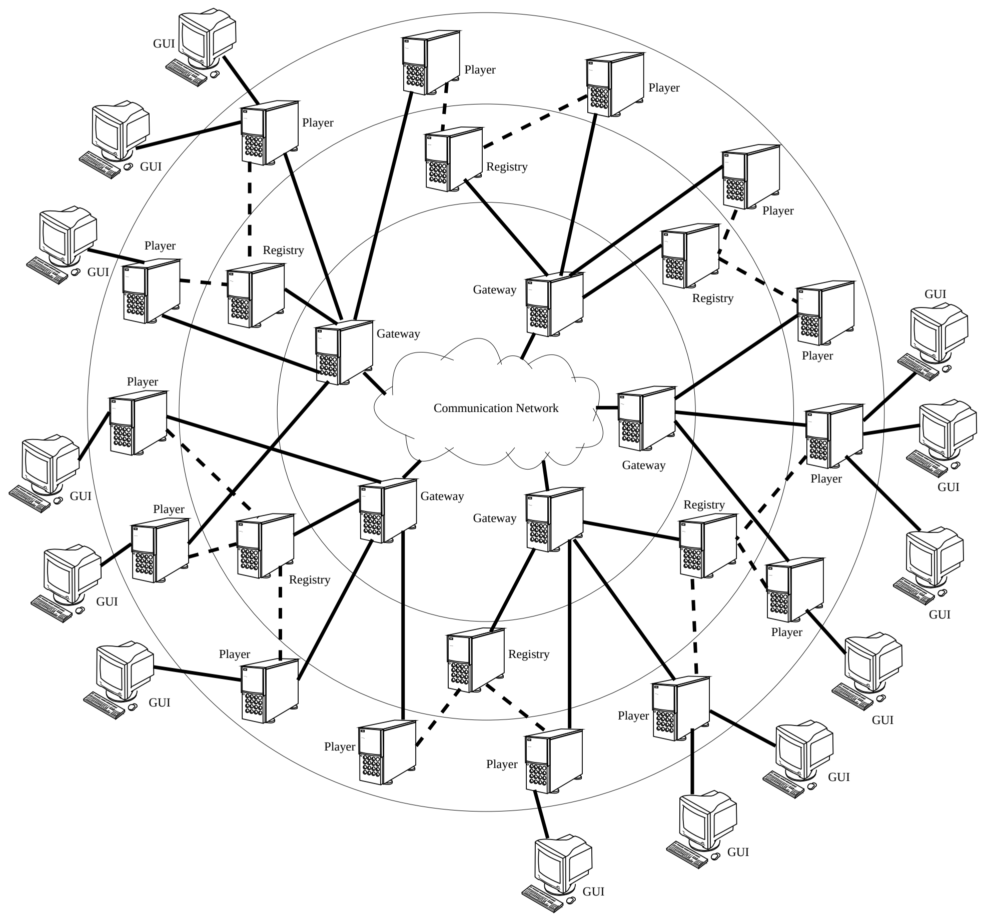

Figure 2: Possible realization of the platform

functionality described in the LLC layer in Subsection 4.1. The specific hosts connected to this network that concern us are a set of ***gateway hosts that run the BTTF and the HLC layers***.

The ring of hosts around the core in Figure 2 contains the set of ***hosts that run the local registries***. Every local registry has a primary connection to a gateway host in the core. Thus, the full reachability of the gateway hosts in the core ensures full reachability among local registries.

The next ring of hosts in Figure 2 contains ***hosts that run player processes***. Each player process establishes an initial link (dotted lines) with a local registry (whose address it obtains from a local forum) to register. As part of this registration process, its local registry provides the address of a gateway host with which the player process then establishes its primary communication link (solid lines) for the rest of the game.

Finally, the outermost ring in Figure 2 consists merely of ***computers that run GUI programs*** that link to their respective player processes.

This 'ring structure' provides a multiple protection scheme against manipulations by the players. First, the assignment of a gateway host to the player process, provided by the local registries, is done dynamically. So there is no way for a player process to know before-hand which host its local registry will propose as its gateway.

Next, the only messages that pass through a local registry are the ones involving its locally registered players. Likewise, the only messages that pass through a player process are the ones originating from or destined for that specific player. This, as already mentioned in Section 3, automatically prevents manipulation by player processes of messages originating from or destined for other players.

Further, the end users have physical access only to the outermost hosts that run the GUI programs, which severely restricts the range of their potentially dangerous actions. Finally, the separation of the GUI programs from the player processes allows us to run the latter on hosts to which end users do not have physical access.

Note also that the reliance on the registration process allows the users to use the High Level Communication (HLC) layer in a 'safe mode'. In such a mode the users can trust the security of the messages they exchange through a 'public' communications system, by relying on the encryption of the messages using the public key cryptography. This can be achieved, for example, by modifying the first call of the `termination loop`, in action (v) of Subsection 4.4, so that it includes the collection of public keys of the registered players. Subsequent messsages sent by player processes can from that moment on be encrypted with recipients' public keys.

We do assume that the communications network, gateways and local registries run on secure hosts. The security issues involved here are generic and independent of the properties and characteristics of any specific mechanism in which the players may engage. However, we do not assume that player processes run on secure hosts, thus allow for the possibility that they can be tampered with or tailor made, to let their end users cheat. In the next subsection we discuss how to deal with this problem.

5.2 Distributed Policing

One possibility to tamper with the system consists of altering the code of a player process so that it sends to some players a falsified decision or a falsified tax scheme. By ***policing*** we mean here a sequence of actions that will lead to the exclusion of such processes (that we call *dishonest*). The qualification 'distributed' refers to the fact that the policing is done by the player processes themselves, without intervention of any central authority. Below we call a player process *honest* if it multicasts a true tax scheme.

The difficulty in implementing distributed policing lies in the fact that dishonest processes may behave inconsistently. To resolve this problem we make use of registries that are assumed to be reliable. We then modify the sequence of actions of each player process so that it always computes the decision and the tax scheme but sends them only to its local registry. The local registry then dispatches the tax scheme on behalf of its sender to all player processes mentioned in the tax scheme. As a trusted intermediary, the registry ensures that the same tax scheme is sent to all player processes involved, and that no player process can send more than one tax scheme in a single phase.

The resulting sequence of actions performed by each player process p_i is now as follows, where the new steps are (vi)–(viii):

(i) process p_i representing player i is created and assigned a globally unique name,

(ii) p_i obtains player i's type,

(iii) p_i signs in at the local registry `r` in its region,

(iv) if p_i receives the confirmation of the registration it broadcasts player i's type and otherwise it terminates,

(v) p_i performs the `termination loop`,

(vi) p_i computes the decision and the tax scheme of the players and sends this information to its local registry, requesting the latter to dispatch this information, on its behalf, to all other player processes,

(vii) p_i collects the decisions and the tax schemes dispatched by all other player processes. By comparing them with the true decision and tax scheme computed by itself, p_i identifies the set of honest player processes, $honest_i$,

(viii) p_i performs the `termination loop` and terminates.

Note that upon termination each player process p_j has the same set $honest_j$. This way all honest processes gain the common knowledge of their own identities, which makes it possible for them to 'reconvene' in the case a falsified tax scheme was sent, or to finalize the tax handling with the tax collector otherwise. processes.

5.3 Fault-tolerance

Our system supports fault-tolerance on various levels. First, the `llsend(m, r)` operation of the Lower Level Communication (LLC) layer returns a Boolean value that indicates its success or failure, so it provides a provision for recovery. Next, the BTTF algorithm from the BTTF layer detects persistent process failures.

Additionally, thanks to the duplication of the computation by all players, we can easily modify the design to support fault-tolerance on the mechanism design level. Namely, suppose that some of the player processes crashed after they broadcast the players' types. This will be discovered by one of the invocations of the *termination loop* of the player process. One can modify this loop by including in it a provision that in case of a discovery of such a crash the computation of the player process restarts the computation with action (iv).

Accordingly, each player process that did not crash can simply ignore discovery of such crashes and compute the decision and the tax scheme anyway. Such an approach is meaningful when to take a decision a quorum or a sufficient funding level is needed and the broadcast types show that none is present.

6 Examples

We used our distributed mechanism design system in a number of test cases that we now briefly describe. Each of them, is implemented as an instantiation of the player process layer described in Subsection 4.4.

6.1 Vickrey auction with redistribution

In Vickrey auction there is a single object for sale which is allocated to the highest bidder who pays the second highest bid. We consider here the proposal of [4] in which the highest bidder redistributes some amounts from his payment to other players. This minimizes the overall tax.

First we model Vickrey auction as the following decision problem $(D, \Theta_1, \ldots, \Theta_n, v_1, \ldots, v_n, f)$:

- $D = \{1, \ldots, n\}$,
- each Θ_i is the set $\mathcal{R}_+$ of non-negative reals; $\theta_i \in \Theta_i$ is player i's valuation of the object,
- $v_i(d, \theta_i) := \begin{cases} \theta_i & \text{if } d = i \\ 0 & \text{otherwise} \end{cases}$
- $f(\theta) := i$,

  where $\theta_i = \max_{j \in [1..n]} \theta_j$ and[1] $\forall j \in [i+1..n]\ \theta_j < \theta_i$.

Here decision $d \in D$ indicates to which player the object is sold. By definition f is an efficient decision rule. Below, given a sequence s of reals we denote by $[s]_k$ the kth largest element in this sequence. For example, for $\theta = (1, 5, 2, 3, 2)$ we have $[\theta_{-2}]_2 = 2$ since $\theta_{-2} = (1, 2, 3, 2)$.

The payments (taxes) in Vickrey auction are realized by applying the VCG mechanism, which yields

$$t'_i(\theta) := \begin{cases} -[\theta]_2 & \text{if } f(\theta) = i \\ 0 & \text{otherwise} \end{cases}$$

To formalize the redistribution scheme of [4] in our framework we combine each tax t'_i with the following function h_i (to ensure that it is well-defined we need to assume that $n \geq 3$):

$$h_i(\theta_{-i}) := \frac{[\theta_{-i}]_2}{n}$$

that is, by using

$$t_i(\theta) := t'_i(\theta) + h_i(\theta_{-i}).$$

Note that this yields a Groves mechanism since by the definition of the VCG mechanism for specific functions $h'_1, \ldots, h'_n$

$$t'_i(\theta) := h'_i(\theta_{-i}) + \sum_{j \neq i} v_j(f(\theta), \theta_j)$$

[1]In case of a tie we allocate the object to the player with the highest index.

and consequently

$$t_i(\theta) = (h_i + h'_i)(\theta_{-i}) + \sum_{j \neq i} v_j(f(\theta), \theta_j).$$

The resulting mechanism is feasible since for all $i \in [1..n]$ and θ we have $[\theta_{-i}]_2 \leq [\theta]_2$ and as a result

$$\sum_{i=1}^{n} t_i(\theta) = \sum_{i=1}^{n} t'_i(\theta) + \sum_{i=1}^{n} h_i(\theta_{-i}) = \sum_{i=1}^{n} \frac{-[\theta]_2 + [\theta_{-i}]_2}{n} \leq 0.$$

Let, given the sequence θ of submitted bids (types), π be the permutation of $1, \ldots, n$ such that $\theta_{\pi(i)} = [\theta]_i$ for $i \in [1..n]$ (where we break the ties by selecting players with the higher index first). So the ith highest bid is by player $\pi(i)$ and the object is sold to player $\pi(1)$. Then

- $[\theta_{-i}]_2 = [\theta]_3$ for $i \in \{\pi(1), \pi(2)\}$,
- $[\theta_{-i}]_2 = [\theta]_2$ for $i \in \{\pi(3), \ldots, \pi(n)\}$,

so the above mechanism boils down to the following payments by player $\pi(1)$:

- $\frac{[\theta]_3}{n}$ to player $\pi(2)$,
- $\frac{[\theta]_2}{n}$ to players $\pi(3), \ldots, \pi(n)$,
- $[\theta]_2 - \frac{2}{n}[\theta]_3 - \frac{n-2}{n}[\theta]_2 = \frac{2}{n}([\theta]_2 - [\theta]_3)$ to the tax collector,

that is, it does indeed coincide with the scheme of [4].

6.2 Unit demand auction

We now consider an auction with multiple items offered for sale. We assume that there are n players and m items and that each player submits a valuation for each item. The items should be allocated in such a way that each player receives at most one of them and the aggregated valuation is maximal.

This auction can be modelled as the following decision problem:

- $D = \{f \mid f : A \rightarrow \{1, \ldots, n\}, A \subseteq \{1, \ldots, m\}, f \text{ is 1-1}\}$,
  i.e., each decision is a 1-1 allocation of items to players,

- $\Theta_i = \mathcal{R}_+^m$; $(\theta_{i,1}, \ldots, \theta_{i,m}) \in \Theta_i$ is a vector of player i's valuations of the items for sale,

- $v_i(d, \theta_i) := \begin{cases} \theta_{i,j} & \text{if } d(j) = i \\ 0 & \text{if } \neg\exists j\ d(j) = i \end{cases}$

- $f(\theta') := d$ for which $\sum_{j \in dom(d)} \theta'_{d(j),j}$ is maximal.

Decision rule f is clearly efficient, so Groves Theorem can be used. Our distributed implementation of the corresponding VCG mechanism is again realized as an instance of the player process layer of Subsection 4.4 with the following details concerning computation of the decision and taxes.

When a player has received the types from all the registered players he needs to compute the decision. To this end we use the Kuhn-Munkres algorithm to compute the maximum weighted matching, where the weight associated with the edge (j, i) is the valuation for item j reported by player i. In our implementation we used the Java source code available at `http://adn.cn/blog/article.asp?id=4`

To compute tax for player i according to the VCG mechanism this algorithm needs to be used again, to compute the maximum weighted matching with player i excluded.

6.3 Single minded auction

Next we consider an auction studied in [9] in which there are n players and m items, with each player only interested in a specific set of items (which explains the name of the auction). In our approach we limit ourselves to the situation in which each player i is only interested in a consecutive sequence $a_i, \ldots, b_i$ of the items $1, \ldots, m$, with $1 \leq a_i \leq b_i \leq m$.

We model this as the following decision problem:

- $D = \{f \mid f : A \to \{1, \ldots, n\},\ A \subseteq \{1, \ldots, m\}\}$,

- $\Theta_i = \mathcal{R}_+$; $\theta_i \in \Theta_i$ is player i's valuation for the sequence $a_i, \ldots, b_i$ of the items,

- $v_i(d, \theta_i) := \begin{cases} \theta_i & \text{if } d(j) = i \text{ for all } j \in [a_i, \ldots, b_i] \\ 0 & \text{otherwise} \end{cases}$

- $f(\theta') := d$ for which $\sum_{i: d([a_i, \ldots, b_i]) = \{i\}} \theta'_i$ is maximal, where $d([a_i, \ldots, b_i]) = \{d(j) \mid j \in [a_i, \ldots, b_i]\}$.

So, given an allocation $f \in D$ the goods in the set $\{k \mid f(k) = j\}$ are allocated to player j. Note that alternatively f can be defined by:

$$f(\theta') := d \text{ for which } \sum_{i=1}^{n} v_i(d, \theta'_i) \text{ is maximal.}$$

So f is efficient and consequently Groves Theorem applies. The computations of the decision and of the taxes within the player process layer of Subsection 4.4 involve constructions of the maximum weighted matchings that are computed using a dynamic programming algorithm, details of which are omitted.

6.4 Sequential Groves mechanisms

In the original set up of the decision problem all players announce their types independently. In a modification studied in [2] the types are announced sequentially, in a random order.

Suppose that the random order is $1, \ldots, n$. The crucial difference between the customary set up and the one now considered is that player i knows the types announced by players $1, \ldots, i-1$. In [2] it was shown that in Groves mechanisms used for problems concerned with public projects players have then other dominant strategies than truth-telling (i.e., announcing their true type) and that these strategies can be used to minimize the taxes.

Sequential Groves mechanisms can be implemented by means of our distributed mechanism system using the appropriate locking policy loaded by the local registries. This locking policy takes care that when process p_i receives the confirmation of the registration, it includes its sequence number j and information whether it represents the last player (the latter is needed to use other optimal strategies than truth-telling). Then the `receive(m, t)` and `passiveReceive(m)` functions of p_i are partly blocked so that only the messages sent by processes representing players with sequence number $< j$ can be received, and the `bsend()` function is blocked until p_i has received the types from these $j - 1$ processes.

6.5 Other applications

To test the versatility of our approach we also implemented a number of other examples. These include:

- Vickrey auction,

- a number of examples of decision making concerned with public projects, see [10, Chapter 23],
- Walker mechanism of [19].

In the latter mechanism each player i has a utility function of the form $v_i(q) := b_i(q) - c_i(q)$. Here q is the total amount of public good (for example grass area in a city) produced by the players, $b_i(q)$ is the benefit for player i from the amount of q of public good, and $c_i(q)$ is the cost share player i has to pay.

Each player i reports a real number x_i, which is interpreted as the amount of public good he agrees to produce. Then he receives the payment (tax)

$$t_i(x) := (x_{i+1} - x_{i-1}) \sum_{j=1}^{n} x_j,$$

where we interpret $n+1$ as 1 and $1-1$ as n, that is $i+1$ and $i-1$ are the indices of the right-hand and left-hand neighbours of player i in a ring.

So $x = \sum_{j=1}^{n} x_j$ is the total amount of public good produced and the final utility for player i is of the form $u_i(x) := v_i(x) + t_i(x)$.

This mechanism is not an instance of Groves mechanism and implements the decision not in dominant strategies but in a Nash equilibrium. To implement it we again merely modified the player process layer. To test this mechanism we used specific functions b_i and c_i.

7 Conclusions and future work

In this paper we discussed a design and implementation of a platform that supports distributed mechanism design and that can be customized to specific Internet-based applications.

We believe that the proposed platform clarifies how the design of systems supporting distributed decision making through the Internet can profit from sound and proven principles of software engineering, such as separation of concerns and hierarchical design. The discussed platform is built as a sequence of layers. The lower layers provide support for distributed computing, while the upper ones are concerned only with the matters specific to mechanism design. Specific Internet-based applications can be readily realized by creating a backbone of local registries and selecting appropriate registration details.

We found that the division of the software into layers resulted in a flexible design that could be easily customized to specific mechanisms proposed in the literature, such as (sequential) Groves mechanisms and Walker mechanism, and to specific applications, such as various forms of auctions. For example, our distributed implementation of Vickrey auction required modification of a module of only 60 lines of code. Additionally, this layered architecture offers a multi-level protection scheme against manipulations, distributed policing and supports fault-tolerance.

We also provided evidence that software engineering in the area of multiagent systems can profit from the techniques developed in the area of distributed computing, for example broadcasting in an environment with an unknown number of processes, distributed termination and barrier synchronization.

In our work we have not dealt with the problem of false-name bids, see [20], that needs to be addressed anew in the context of distributed implementations. This is the subject of our current research. Also, we plan to use our system to implement continuous double auctions.

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Appendix I

We explain here the details of the reduced tax scheme algorithm mentioned in Section 3. Intuitively, this algorithm determines given the tax vector $(t_1, \ldots, t_n)$ 'who pays how much to whom'.

We consider a list of players, each with his tax, and assume that the tax vector is feasible, that is the total sum of taxes is non-positive. This means that the claims of the players whose taxes are positive can be financed by the players whose taxes are negative.

First the players are divided into two lists, $A^0_{neg}, \ldots, A^k_{neg}$, consisting of players whose taxes are negative (i.e., those who should pay the taxes) and $A^0_{pos}, \ldots, A^m_{pos}$ consisting of players whose taxes are strictly positive (i.e., those who should be paid). Players whose tax is 0 are omitted.

We start with player A^0_{neg} and compare the absolute value of his tax, $|t^0_{neg}|$, with the tax t^0_{pos} of player A^0_{pos}.

If $|t^0_{neg}| \geq t^0_{pos}$, player A^0_{neg} pays the amount t^0_{pos} to player A^0_{pos}. This changes the tax of player A^0_{neg} from t^0_{neg} to $t^0_{neg} + t^0_{pos}$. The process is now repeated with player A^0_{neg} and the next unpaid player, A^1_{pos}.

If $|t^0_{neg}| < t^0_{pos}$, then player A^0_{neg} pays the amount $|t^0_{neg}|$ to player A^0_{pos}. This changes the tax of player A^0_{pos} from t^0_{pos} to $t^0_{pos} + t^0_{neg}$. The process is now repeated with the next player who should pay a tax, A^1_{neg}, and player A^0_{pos}.

The loop stops when all players with negative taxes paid. Termination is ensured by the assumption that the tax vector is feasible. If the mechanism is not balanced, upon termination each player that still needs to pay some tax pays it to the tax collector.

The pseudo-code of the algorithm is given in Figure 3.

```
$L_{all}$ is the list of $n$ players;
$A^i$ is the $(i+1)$st player in the list $L_{all}$;
$n_{all}$ is the length of the list $L_{all}$;
$t^i$ is the tax of player $A^i$;
$tax$ is the list representing the computed tax scheme;
for $i = 0$ to $n_{all}$ do
  if $t^i < 0$ then
    append $A^i$ to the list $L_{neg}$;
  end if
  if $t^i > 0$ then
    append $A^i$ to the list $L_{pos}$;
  end if
end for;
let $A^j_{neg}$ be the $(j+1)$st player in the list $L_{neg}$;
$t^j_{neg}$ is the tax of player $A^j_{neg}$;
let $A^k_{pos}$ be the $(k+1)$st player in the list $L_{pos}$;
$t^k_{pos}$ is the tax of player $A^k_{pos}$;
let $n_{neg}$ be the length of the list $L_{neg}$;
let $n_{pos}$ be the length of the list $L_{pos}$;
let $t_{cursum}$ be the current sum of all the negative taxes not yet paid;
if $n_{neg}$ != 0 then
  $k = 0$; $j = 1$; $t_{cursum} = t^0_{neg}$;
  while $j \leq n_{neg}$ and $k < n_{pos}$ do
    if $|t_{cursum}| \geq t^k_{pos}$ then
      player $j-1$ pays player $k$
      $amount = t^k_{pos} - (|t_{cursum}| - |t^{j-1}_{neg}|)$;
      $t^{j-1}_{neg} = t^{j-1}_{neg} + (t^k_{pos} - (|t_{cursum}| - |t^{j-1}_{neg}|))$;
      $t_{cursum} = t^{j-1}_{neg}$;
      $k = k + 1$;
      if $t_{cursum} == 0$ then
        $t_{cursum} = t^j_{neg}$; $j = j + 1$;
      end if
    else
      player $j-1$ pays player $k$ $amount = |t^{j-1}_{neg}|$;
      $t_{cursum} = t_{cursum} + t^j_{neg}$; $j = j + 1$;
    end if
    $tax = tax+(j-1, k, amount)$;
  end while
end if
```

Figure 3: The algorithm to compute reduced tax scheme

Appendix II

In this appendix we illustrate a sample interaction with the platform. We assume that each player chooses from the pull down menu a single minded auction, discussed in Section 6.3. We consider a specific instance with

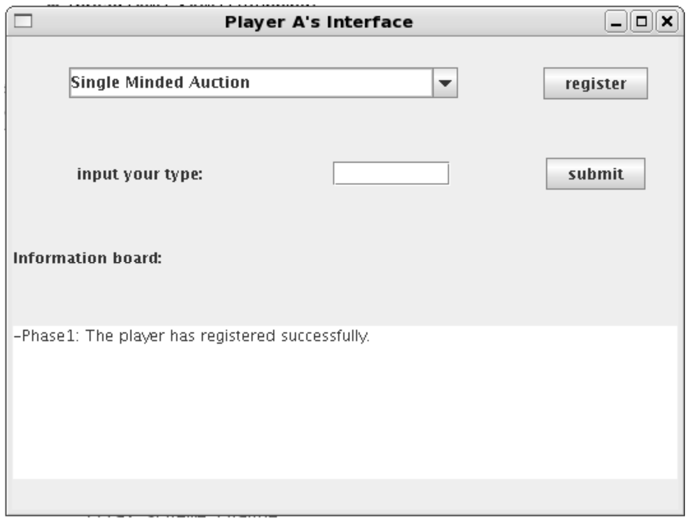
- 5 players,
- 3 items for sale,
- the following players bids: A: 20:(1,2), B: 50:(3), C: 32:(2), D: 60:(2,3), E: 19:(1),

  that is, player A bids 20 for the bundle (1,2), etc.

The registration process was taken care of by creating two local registries. In this example, the generated allocation is: (3:B, 28), (2:C, 10), (1:E, 0), that is item 3 is sold to player B who pays for it to the tax collector 28, etc.

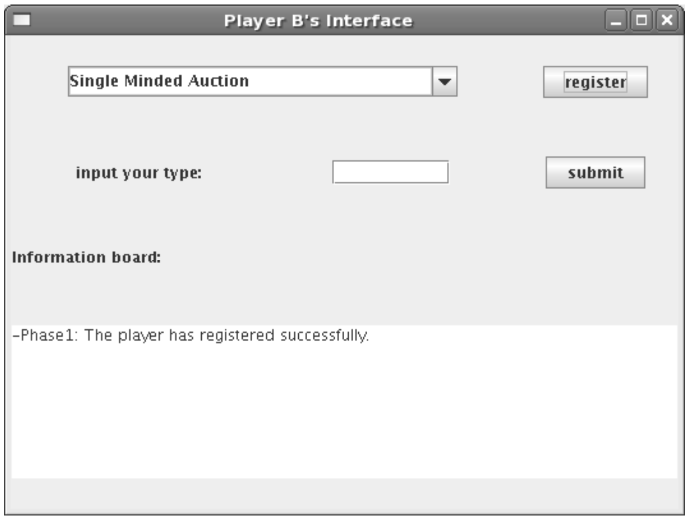
The interaction with the system is presented in Figures 4 – 9 below. The first two figures depict phase 1 which consists of the registration process for players A and B. The 2nd phase, depicted in Figures 6 and 7, is type submission that takes place after the registration is accepted.

The 3rd phase consists of the computation of the tax scheme, its multicasting of it to other players and (in case of unbalanced mechanism) payment of the remaining taxes to the tax collector. The 4th phase consists of receiving by the players information from the tax collector about the overal tax received by it. These two phases are depicted in Figures 8 and 9. They show the difference in computation between fast players (here player A) and slow players (here player B). In this example, in phase 3, the tax scheme was only computed by the fast player, A, who subsequently multicast it.



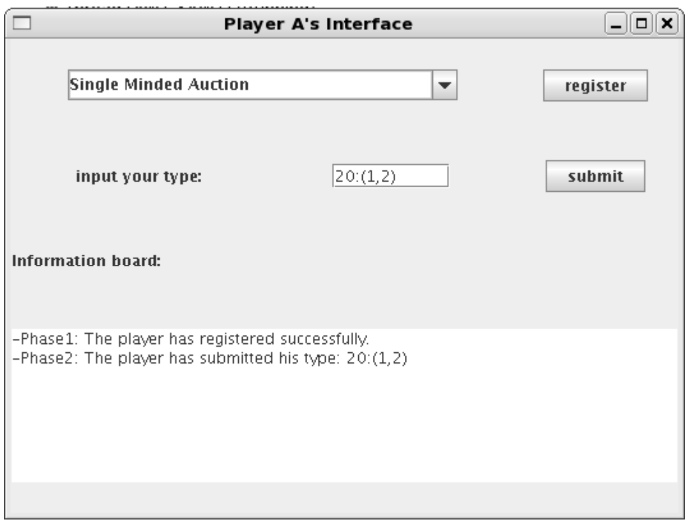
-Phase1: The player has registered successfully.

Figure 4: Phase 1: player A



-Phase1: The player has registered successfully.

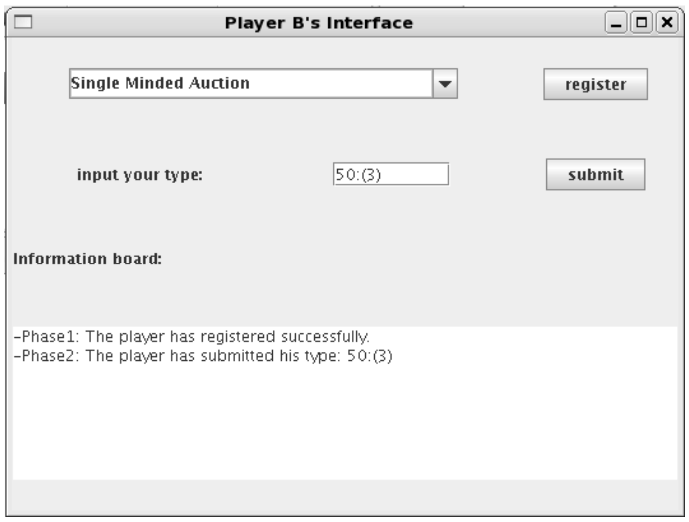
Figure 5: Phase 1: player B



20:(1,2)

```
-Phase1: The player has registered successfully.
-Phase2: The player has submitted his type: 20:(1,2)
```

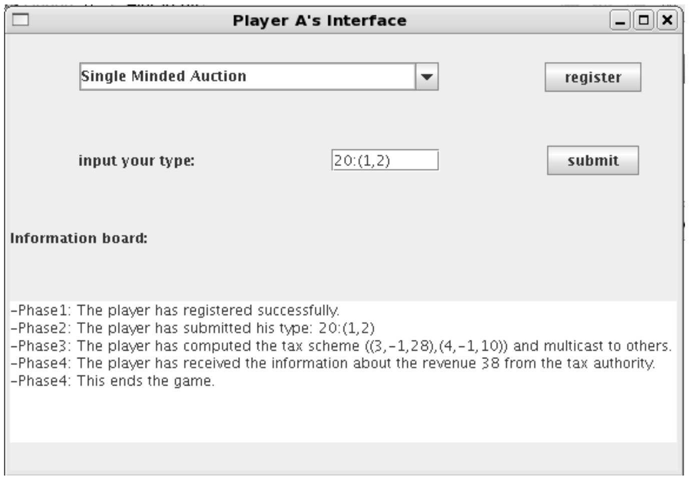
Figure 6: Phase 2: player A



50:(3)

```
-Phase1: The player has registered successfully.
-Phase2: The player has submitted his type: 50:(3)
```

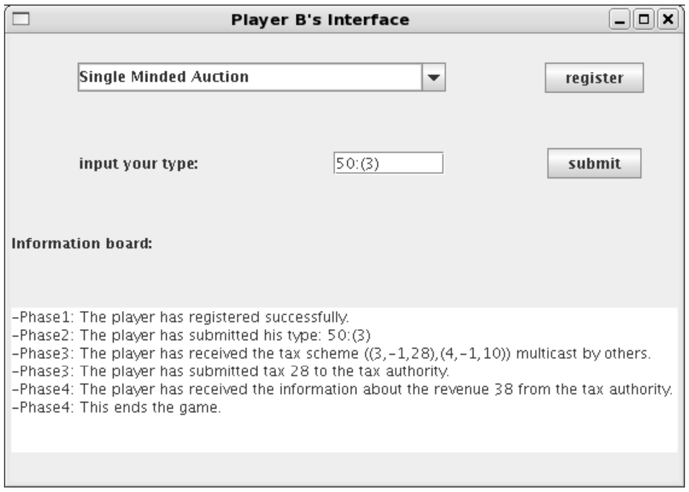
Figure 7: Phase 2: player B



20:(1,2)

```
-Phase1: The player has registered successfully.
-Phase2: The player has submitted his type: 20:(1,2)
-Phase3: The player has computed the tax scheme ((3,-1,28),(4,-1,10)) and multicast to others.
-Phase4: The player has received the information about the revenue 38 from the tax authority.
-Phase4: This ends the game.
```

Figure 8: Phases 3 & 4: player A



50:(3)

```
-Phase1: The player has registered successfully.
-Phase2: The player has submitted his type: 50:(3)
-Phase3: The player has received the tax scheme ((3,-1,28),(4,-1,10)) multicast by others.
-Phase3: The player has submitted tax 28 to the tax authority.
-Phase4: The player has received the information about the revenue 38 from the tax authority.
-Phase4: This ends the game.
```

Figure 9: Phases 3 & 4: player B