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デジタル財の割当てメカニズムにおける問題点

松原　繁夫†

† 日本電信電話株式会社
NTT コミュニケーション科学基礎研究所
〒619–0237 京都府相楽郡精華町光台 2–4

E-mail: †matsubara@cslab.kecl.ntt.co.jp

あらまし ピアツーピアネットワークにおけるファイル共有システムやコンテンツ配送サービスは，デジタル財の新たな取引機会を提供している．ここで，デジタル財とは，ソフトウェア，音声／映像コンテンツ，情報などネットワーク上で直接配送される財を指す．しかし，このようなシステムは，例えば，ただ乗りなどの，エージェントの利己的性質によって引き起こされる問題を抱えている．このような環境において十分な品質のサービスを提供するには，適切な財の割当てを求めることと，エージェントの努力を引き出すことが必要である．しかし，この問題の解決は容易でない．なぜなら，システム設計者はエージェントのサービス提供に要する費用に加えて，エージェントの努力水準も直接観測できないからである．この問題を解決するため，我々は，契約に関してオークションを行う新たなメカニズムを提案する．このメカニズムは，オークションによって効率的な財の割当てを求めた後に，その結果に基づいて適切な契約を計算する．本稿では，提案メカニズムの性質をゲーム理論を用いて解析し，財が 1 つの場合には，エージェントの真実申告を保証することを示す．

キーワード　オークション，契約，電子商取引，ゲーム理論

Some Problems in an Allocation Mechanism for Digital Goods

Shigeo MATSUBARA†

† NTT Communication Science Laboratories
NTT Corporation
2–4 Hikaridai, Seika-cho, Soraku-gun, Kyoto 619–0237 Japan

E-mail: †matsubara@cslab.kecl.ntt.co.jp

Abstract File-sharing systems and content delivery services in peer-to-peer networks offer new opportunities for trading digital goods such as software, audio/video content, and information, which are delivered directly via the network. Unfortunately, these systems involve problems caused by the self-interested nature of agents, an example being the so-called free-riding. To keep the quality of services at a sufficient level, we have to find an efficient allocation of goods and induce each agent's effort. However, solving this problem is difficult because the system designer cannot observe each agent's effort level as well as the agent's cost of providing the services. To solve this problem, we propose a new mechanism that auctions contracts. More specifically, the mechanism first finds an efficient allocation of the goods and then calculates a contract based on the result of the auction. We theoretically analyze the mechanism and demonstrate that the mechanism guarantees that each agent reveals its true information in a single good case.

Key words auction, contract, electronic commerce, game theory

1 Introduction

The Internet offers new opportunities for trading digital goods such as software, audio/video content, and information, which are delivered directly via the network. An example is file-sharing services in peer-to-peer networks [1]. These services allow individuals to share files residing on their own PC, which provides an efficient use of digital goods.

To achieve efficient operation of such a system, it is necessary to give individuals an appropriate economic incentive to produce goods and provide them to others, since their participation is voluntary. This research aims to develop an appropriate incentive mechanism by using agent technologies and game theory.

A designer of file-sharing systems needs to allocate digital goods among participant agents in a way that minimizes the total operation cost. Here, we assume that different agents incur different costs for storing goods and providing them to others. Consequently, there exists the problem of the designer not being able to learn the true value of each agent's cost, namely, the problem of asymmetric information. One promising way to deal with asymmetric information and attain an efficient allocation of goods is an auction. Recently, auction mechanisms have been actively studied in the fields of AI and agent technologies [2, 3, 4].

However, in file-sharing systems, it is not sufficient to only allocate the goods. To keep the quality of services at an appropriate level, the designer has to induce each agent to behave appropriately. For example, if the load of service provision becomes large, the corresponding agent has to assign additional CPU resources to the task of file-sharing services, although no agent is motivated to provide additional resources without compensation. To solve this problem, the designer needs to give agents an incentive, e.g., by paying some compensation money. However, it is not easy to determine the appropriate amount of compensation money because the designer cannot directly observe the amount of CPU resources each agent assigns to the file-sharing task.

One solution to this problem is to give a reward according to the result of service provision, namely, to give a higher reward if service provision succeeds. The problem that needs to be solved is to minimize the payments while still guaranteeing each agent's voluntary participation, and this problem has been discussed in contract theory [5].

From the above discussion, we have developed a way to keep the quality of services at an appropriate level that keeps the operation cost lower when a designer cannot directly observe the behavior of participant agents as well as their information (the cost incurred for providing services). This is a quite difficult problem because we have to solve two problems simultaneously: (1) how to allocate the goods among agents, and (2) what kind of contract to make for inducing each agent's appropriate behavior.

Especially in the allocation problem of multiple goods, it is difficult to devise a contract that maximizes the designer's profit. Therefore, we propose an approximation method in which contracts are auctioned. More specifically, we first calculate an allocation of the goods so that social surplus is maximized in terms of the storing cost and then calculate a contract so that the designer's profit becomes sufficiently large. There is related research by Laffont and Tirole, although their problem setting is different from ours [6]. In addition, we analyze the property of the proposed mechanism based on game theory.

Previously, many multiagent researchers have discussed a contract net protocol for solving task allocation problems [7]. While these research efforts have not given attention to how to motivate each agent to carry out its contract, this paper does so by dealing with the implementation problem as well as the allocation problem. This is the original achievement of this paper.

In Section 2, we describe the formal model, and in Section 3, we deal with symmetric information between a designer and participant agents. In Sections 4 and 5, we deal with asymmetric information. More specifically, Section 4 describes performance with a single good, while Section 5 describes performance with multiple goods. Finally, Section 6 gives our concluding remarks.

2 Model

This section gives a formal model to enable rigorous discussions. In the trading place, there is a contractee agent and multiple contractor agents. [1] The contractee agent has multiple goods (tasks) to be allocated.

Assumption 1 *For contractor agent i, it costs $\beta_i(k_i)$ to provide services related to the allocated*

[1] In game theory, the former is called a principal, while the latter are called agents.

goods k_i. This cost is measured by the utility unit introduced below.

This is the cost for agent i to provide services related to the allocated goods by using its excess resources. The amount of the cost depends on contractor agent i's ability. Therefore, we call this the agent's technology. The smaller the cost is, the higher the technology level is. If there is no fear of causing any confusion, we designate the cost $\beta_i(k_i)$ by β_i.

In addition, contractor agent i can re-assign its resources used for another task to service provision for k_i. For example, assigning more CPU resources enables a quick response to a service request, although agent i suffers a loss by suspending the other task.

Assumption 2 *The amount of the additional assignment of resources by contractor agent i is called the agent's effort, which is denoted by e_i. e_i is chosen from the interval $[\underline{e}, \overline{e}]$. We assume that agent i's loss caused by its effort e_i is equal to e_i.*

Assumption 3 *The result of service provision takes one of two states: success or failure.*

Assumption 4 *The result of service provision by contractor agent i is determined probabilistically based on agent i's technology and effort. Let $p(\beta_i, e_i)$ denote the probability for success in providing services when agent i's technology is equal to β_i and its effort is equal to e_i.*

Assumption 5 *The probability for success in providing services by contractor agent i, $p(\beta_i, e_i)$, is an increasing concave function of agent i's effort e_i and a decreasing concave function of agent i's technology β_i. Additionally, if $\beta^1 < \beta^2$, $p'(\beta^1, e_i) < p'(\beta^2, e_i)$.*

Here, $p'(\beta_i, e_i)$ denotes the first-order partial derivative with respect to e_i. The assumption that if $\beta^1 < \beta^2$, $p'(\beta^1, e_i) < p'(\beta^2, e_i)$ means that if agent i has a high technology level, it becomes difficult to increase the probability of success in providing services.

Assumption 6 *The contractee agent cannot observe contractor agents' technologies and efforts.*

Assumption 7 *The contractee agent knows the probability function of success in providing services.*

This means that the contractee agent cannot learn the individual information of each contractor agent, but can learn statistical information of a group of contractor agents.

Assumption 8 *The contractee agent pays a reward w_i^H to contractor agent i if the agent's service provision succeeds and pays a reward w_i^L if its service provision fails.*

Let $u(w_i)$ denote contractor agent i's utility of obtaining a reward w_i. Contractee agent i's expected utility, $U_i(e_i)$, is defined as follows.

Definition 1

$$U_i(e_i) = p(\beta_i, e_i)u(w_i^H) + (1 - p(\beta_i, e_i))u(w_i^L) - \beta_i - e_i$$

Assumption 9 *To simplify discussion, we assume that the utility function u is identical for all contractor agents, and set $u(0) = 0$ as a datum point. In addition, u is monotonically increasing and concave. This means that the contractor agent is risk-averse.*

Definition 2 *The objective function of the contractee agent is represented as follows.*

$$\max \sum_n -(1 - p(\beta_i, e_e))q - p(\beta_i, e_i)w_i^H - (1 - p(\beta_i, e_i))w_i^L$$

where n represents the number of contractor agents.

In this expression, the first term represents the decrease of the contractee agent's profit caused by the failure of service provision, and the second and third terms represent the payment to contractor agents. If agent i is not allocated any goods, $w_i^H = w_i^L = 0$. Therefore, the contractee agent is risk-neutral.

3 Symmetric information: a single good

This paper mainly focuses on the case of asymmetric information, namely, where a contractee agent cannot directly observe the contractor agents' technologies and efforts. However, as a reference point, this section deals with the case of symmetric information and investigates what kind of contract is entered into. We assume that the number of goods is one.

Our objective is to obtain a contract that maximizes the contractee agent's profit. In the case of symmetric information, it is known that paying a fixed reward, $w_i^H = w_i^L$, is sufficient for solving the problem [5]. We designate this value as w_i. To guarantee that contractor agent i voluntary signs a contract, it is necessary that this agent's utility does not decrease by entering into a contract. This is called the participation constraint and is represented as follows.

$$u(w_i) - \beta_i - e_i \geq 0 \qquad (1)$$

Under this condition, we find e_i and w_i so that the contractee agent's objective function is maximized. The contractee agent's objective function can be written as follows.

$$\max(-(1 - p(\beta_i, e_e))q - w_i) \qquad (2)$$

Expression (2) means that if the effort level of e_i becomes larger, the probability of success in providing services, $p(\beta_i, e_i)$, becomes larger, and thus the profit reduction, $(1 - p(\beta_i, e_e))q$, caused by the failure of service provision becomes smaller. On the other hand, expression (1) means that if e_i becomes larger, the contractee agent has to pay a larger reward w_i. Therefore, there exists an appropriate effort level of e_i.

From expression (1), it is obvious that we can reduce the reward w_i by choosing the smallest cost β_i. Therefore, it is best for the contractee agent to make a contract with a contractor agent with the smallest β_i. In the contract, the contractee agent pays w_i to the contractor agent i if agent i attains the effort level of e_i, otherwise, it pays nothing.

Such a contract is feasible because the contractee agent can observe the contractor agent's effort level. When the contractee agent cannot observe the contractor agent's effort level, if the contractee agent pays a fixed amount of reward, the contractor agent only attains the least level of effort.

To solve this problem, we pay different rewards corresponding to the result of service provision. A problem to be solved is what kind of contract increases the contractee agent's profit. This is discussed in the next section.

4 Mechanism for determining an allocation/contract: a single good case

In this section, we propose a new mechanism that determines the allocation of the goods and contracts (the amounts of reward). For easy understanding, this section deals with a single good, and the next section extends it to multiple goods.

As mentioned above, it is difficult to obtain a contract that maximizes the contractee agent's profit, especially in the case of multiple goods. Therefore, as an approximation method, we develop an allocation/contract method that first obtains an allocation that maximizes social surplus in terms of the contractor agents' cost and then calculates contracts based on the obtained allocation in the first step.

4.1 Mechanism for determining an allocation/contract

The procedure of our developed mechanism is as follows.

1. Each contractor agent reports its cost of providing services for the good (which may or not be true) to the contractee agent. Each cost is measured by a unit of utility. Any reported values of other agents remain undisclosed to the contractor agent.

2. The contractee agent finds the contractor agent i who reported the minimum cost.

3. The contractee agent calculates a contract (w_i^H, w_i^L) and offers it to agent i.

4. Contractor agent i decides whether to accept the contract (w_i^H, w_i^L).

5. If contractor agent i rejects the contract (w_i^H, w_i^L), the good is not allocated to any agent.

The calculation method of the contract (w_i^H, w_i^L) in step 3 is described in the next section.

4.2 Behavior of a contractor agent

In this subsection, we examine what kind of contract should be offered to a contractor agent to induce it to select an effort level of e. To induce agent i to select an effort level of e, the following incentive compatibility constraint must hold.

$$\begin{aligned} & p(\beta_i, e)u(w_i^H) + (1 - p(\beta_i, e))u(w_i^L) - \beta_i - e \\ \geq \; & p(\beta_i, e_i)u(w_i^H) + (1 - p(\beta_i, e_i))u(w_i^L) \\ & - \beta_i - e_i \quad (where\ e_i \neq e) \end{aligned}$$

This constraint means that the utility obtained by selecting an effort level of e must be larger than or equal to that obtained by selecting another effort level.

Concerning the incentive compatibility constraint, contract theory tells us that if both the monotone likelihood ratio condition (MLRC) and the convexity of distribution function condition (CDFC) hold, we can apply the first-order approach [5]. MLRC means that the larger the probability of success in providing services is, the larger the likelihood that a higher effort level is selected. CDFC intuitively means that the contractor agent's marginal profit for an additional effort probabilistically decreases.

Because this paper assumes that the number of possible results of service provision is two and the probability $p(\beta_i, e_i)$ is an increasing concave function of e_i, we can conclude that the two conditions of MLRC and CDFC hold. Therefore, we can apply the first-order approach. The first-order approach means that the first-order partial derivative of contractor agent i's utility with respect to e_i is equal to 0. That is, the following expression must hold.

$$p'(\beta_i, e_i)(u_i(w_i^H) - u_i(w_i^L)) = 1 \tag{3}$$

Next, we examine the participation constraint. As mentioned above, the participation constraint means that no contractor agent suffers any loss by signing a contract. If the participation constraint does not hold, contractor agents do not sign a contract. Here, we assume that if a contractor agent does not have any goods, its utility is equal to 0. Therefore, the participation constraint is represented as follows.

$$p(\beta_i, e_i)u(w_i^H) + (1 - p(\beta_i, e_i))u(w_i^L) - \beta_i - e_i = 0 \tag{4}$$

From the two conditions (3) and (4), the amounts of rewards are calculated as follows.

$$\begin{aligned} u(w_i^H) &= \beta_i + e_i + \frac{1 - p(\beta_i, e_i)}{p'(\beta_i, e_i)} \\ u(w_i^L) &= \beta_i + e_i - \frac{p(\beta_i, e_i)}{p'(\beta_i, e_i)} \end{aligned}$$

4.3 Behavior of a contractee agent

In section 4.2, we obtain a contract (w_i^H, w_i^L) that induces contractor agent i to select an effort level of e_i. Based on this result, we examine what effort level needs to be set in order to maximize the contractee agent's profit.

The objective function of the contractee agent is given as follows.

$$\begin{aligned} \max_{e_i}(&-(1 - p(\beta_i, e_i))q \\ &- p(\beta_i, e_i)w_i^H - (1 - p(\beta_i, e_i))w_i^L) \end{aligned}$$

Therefore, the best contract for the contractee agent is obtained by calculating the e_i that maximizes the above objective function and substituting the obtained e_i into the expressions of w_i^H and w_i^L. Here, let e_i^* denote the e_i that maximizes this objective function. e_i^* is used in the next section.

4.4 Properties of the mechanism

In the discussion in sections 4.2 and 4.3, we assume that we use the declared value of β_i for calculating the amounts of rewards. However, contractor agent i may report a false value of β_i. As shown in proposition 2, contractor agent i can obtain additional profit by overstating the value of β_i. If contractor agents declare false values and there is no equilibrium, we cannot predict what allocation is realized and how much profit the contractee agent can obtain. Therefore, to induce a contractor agent's truth declaration, we use the second highest declared value of β_j $(j \neq i)$ instead of the highest declared value of β_i. We designate the second highest declared value of β_i as β_i^*.

We insert the following procedure into the mechanism proposed in section 4.1.

2.5 Set the value of β_i to β_i^*.

In this case, contractor agent i selects an effort level of e_i that satisfies the following expression.

$$p'(\beta_i, e_i)\frac{1}{p'(\beta_i^*, e_i^*)} = 1 \tag{5}$$

Therefore, it is no longer guaranteed that contractor agent i selects e_i^*. However, the following condition holds.

Proposition 1 *$e_i \leq e_i^*$ holds.*

Proof From the assumption on the probability of success in providing services $p(\beta_i, e_i)$, namely, $p(\beta_i, e_i)$ is an increasing concave function of e_i and if $\beta^1 < \beta^2$, then $p'(\beta^1, e_i) < p'(\beta^2, e_i)$, it is obvious that the proposition holds. □

In this case, the participation constraint holds.

Proposition 2 *Even if we calculate a contract by using β_i^* as the value of β_i, the participation constraint of contractor agent i still holds.*

Proof Let $e_i^{(1)}$ denote the value of e_i that satisfies expression (5). Here, $U_i(e_i^{(1)}) \geq U_i(e_i^*)$ holds. If contractor agent i selects an effort level of e_i^*, expected utility, $U_i(e_i^*)$, is calculated as follows.

$$\begin{aligned}
&p(\beta_i, e_i^*)u(w_i^H) + (1 - p(\beta_i, e_i^*))u(w_i^L) - \beta_i - e_i^* \\
&= p(\beta_i, e_i^*)(\beta_i^* + e_i^* + \frac{1 - p(\beta_i^*, e_i^*)}{p'(\beta_i^*, e_i^*)}) \\
&\quad + (1 - p(\beta_i, e_i^*))(\beta_i^* + e_i^* - \frac{p(\beta_i^*, e_i^*)}{p'(\beta_i^*, e_i^*)}) \\
&\quad - \beta_i - e_i^* \\
&= \beta_i^* - \beta_i + \frac{1}{p'(\beta_i^*, e_i^*)}(p(\beta_i, e_i^*) - p(\beta_i^*, e_i^*))
\end{aligned}$$

Because $\beta_i \leq \beta_i^*$ holds, $p(\beta_i, e_i^*) > p(\beta_i^*, e_i^*)$ holds. Therefore, we obtain that $U_i(e_i^*) > 0$, and thus the participation constraint of contractor agent i is satisfied. □

Proposition 3 *A contractee agent reports its true value of β_i.*

Proof First, we examine the case where contractor agent i wins the auction if it declares a true value. Contractor agent i cannot manipulate β_i^* because β_i^* is a value reported by another agent. Therefore, even if agent i overstates the value of β_i, as long as it is the winner of the auction, β_i^* does not change. Therefore, expected utility of agent i does not change. If agent i understates the value of β_i, it cannot obtain any additional utility because β_i^* does not change.

Next, we examine the case where contractor agent i loses the auction if it declares a true value. If the contractor agent understates the value of β_i and becomes the winner of the auction, $\beta_i > \beta_i^*$ holds. From the same discussion in the proof of proposition 1, we can obtain $e_i > e_i^*$ in this case.

Let $e_i^{(1)}$ denote the value of e_i that satisfies expression (5). Contractor agent i's expected utility U_i takes the maximum value at an effort level of $e_i^{(1)}$. $U_i(e_i^{(1)})$ is calculated as follows.

$$\begin{aligned}
&p(\beta_i, e_i^{(1)})u(w_i^H) + (1 - p(\beta_i, e_i^{(1)}))u(w_i^L) \\
&\quad - \beta_i - e_i^{(1)} \\
&= \beta_i^* - \beta_i + e_i^* - e_i^{(1)} \\
&\quad + \frac{1}{p'(\beta_i^*, e_i^*)}(p(\beta_i, e_i^{(1)}) - p(\beta_i^*, e_i^*))
\end{aligned}$$

From the assumption on the probability $p(\beta_i, e_i)$, the following inequalities hold.

$$p'(\beta_i^*, e_i^{(1)}) < \frac{p(\beta_i^*, e_i^{(1)}) - p(\beta_i^*, e_i^*)}{e_i^{(1)} - e_i^*} < p'(\beta_i^*, e_i^*) \tag{6}$$

By transforming this expression, the following inequality is obtained.

$$\begin{aligned}
e_i^{(1)} - e_i^* &> \frac{p(\beta_i^*, e_i^{(1)}) - p(\beta_i^*, e_i^*)}{p'(\beta_i^*, e_i^*)} \\
&> \frac{p(\beta_i, e_i^{(1)}) - p(\beta_i^*, e_i^*)}{p'(\beta_i^*, e_i^*)}
\end{aligned}$$

By substituting this inequality for the expression of the expected utility $U_i(e_i)$, we can obtain the following inequality.

$$\begin{aligned}
U_i(e_i^{(1)}) &< \beta_i^* - \beta_i + e_i^* - e_i^{(1)} \\
&\quad + e_i^{(1)} - e_i^* \\
&= \beta_i^* - \beta_i \\
&< 0
\end{aligned}$$

Therefore, the expected utility of $U_i(e_i^{(1)})$ becomes negative, namely, contractor agent i cannot obtain positive utility by understating its value of β_i. □

5 Mechanism for determining an allocation/contract: multiple goods case

5.1 Mechanism for determining an allocation/contract

Here, we show a mechanism for the multiple goods case, outlined in the following procedure.

1. Each contractor agent reports its cost of providing services for bundles of goods (which may or may not be true) to the contractee agent. Each cost is measured by a unit of utility. Any declared values of other agents remain undisclosed to the contractor agent.

2. The contractee agent calculates the allocation k^* that minimizes the sum of the reported costs subject to the resource constraint.

3. The contractee agent also calculates the allocation k^*_{-i} that minimizes the sum of costs other than that of agent i subject to the constraint that any goods are not allocated to agent i.

4. The contractee agent offers a contract to contractor agent i such that agent i provides services for the bundle of goods, k^*_i, and receives w^H_i if the service provision succeeds, otherwise agent i receives w^L_i.

5. Contractor agent i determines whether to accept the contract (w^H_i, w^L_i).

6. If contractor agent i rejects the contract (w^H_i, w^L_i), the bundle of k^*_i is not allocated to any agent.

In step 4, the contract (w^H_i, w^L_i) is calculated in a similar way as in section 4.1. The value of $\beta^*_i(k^*_i)$ is set as follows.

$$\beta^*_i(k^*_i) = \sum_{j\neq i} \beta_j(k^*_{-i}) - \sum_{j\neq i} \beta_j(k^*)$$

This expression is the same as in the payment calculation in the generalized Vickrey auction (GVA) [8].

The contractee agent choose e_i so that the following function is maximized.

$$-(1-p(\beta_i, e_i))q \\ - p(\beta_i, e_i)w^H_i - (1-p(\beta_i, e_i))w^L_i$$

5.2 Properties of the mechanism

In section 4.4, we proved that a contractee agent reports its true value of β_i. In this section, we examine whether the same proposition holds in the multiple goods case.

Proposition 4 *Contractor agent i cannot obtain an additional utility by overstating its value of β_i if the other contractor agent report their true values of β_i.*

Proof (sketch) If contractor agent i overstates its value of β_i and obtains different bundles of goods from that obtained by reporting its true value, the value of β^*_i becomes larger than its true value of β_i. Therefore, from the same discussion in the proof of Proposition 3, we can prove that contractor agent i cannot obtain an additional utility by overstating its value of β_i. □

Unlike a single good case, in the multiple goods case, there is a possibility that contractor agent i can obtain an additional profit by reducing demand, namely, understating its value of β_i and obtaining different bundles of goods from that obtained by reporting its true value. However, we can prove the following proposition.

Proposition 5 *The following inequality is the sufficient condition that contractor agent i reports its true value of β_i.*

$$\frac{1}{p'(\beta^{2*}_i, e^{2*}_i)}(p(\beta^2_i(k^{2*}_i), e^2_i) - p(\beta^{2*}_i(k^{2*}_i), e^2_i)) \\ < \frac{1}{p'(\beta^{1*}_i, e^{1*}_i)}(p(\beta^1_i(k^*_i), e^{1*}_i) - p(\beta^{1*}_i(k^*_i), e^{1*}_i)) \tag{7}$$

where suffix 1 corresponds to the case where contractor agent i reports its true value of β_i, while suffix 2 corresponds to the demand reduction case, namely, where contractor agent i understates its value of β_i. k^{1*}_i represents the allocated goods to agent i in the former case, while k^{2*}_i represents the allocated goods in the latter case.

Proof (sketch)

In the proof of Proposition 2, we demonstrated the following inequality holds.

$$\beta^*_i - \beta_i + \frac{1}{p'(\beta^*_i, e^*_i)}(p(\beta_i, e^*_i) - p(\beta^*_i, e^*_i)) \leq U_i(e^{(1)}_i) \tag{8}$$

As the similar discussion as the proof of Proposition 3, the following inequality hold.

$$p'(\beta^*_i, e^*_i) < \frac{p(\beta^*_i, e^*_i) - p(\beta^*_i, e^{(1)}_i)}{e^*_i - e^{(1)}_i} < p'(\beta^*_i, e^{(1)}_i)$$

By using the first part of the above inequalities, we can obtain the following inequality.

$$U_i(e^{(1)}_i) \leq \beta^*_i - \beta_i + \frac{1}{p'(\beta^*_i, e^*_i)}(p(\beta_i, e^{(1)}_i) - p(\beta^*_i, e^{(1)}_i)) \tag{9}$$

From expressions (8) and (9), if the following inequality holds, it guarantees that the utility obtained by reporting the true value of β_i is larger than that obtained by understating its value of β_i.

$$\beta^{2*}_i - \beta^2_i + \frac{1}{p'(\beta^{2*}_i, e^{2*}_i)}(p(\beta^2_i, e^2_i) - p(\beta^{2*}_i, e^2_i)) \\ < \beta^{1*}_i - \beta^1_i + \frac{1}{p'(\beta^{1*}_i, e^{1*}_i)}(p(\beta^1_i, e^{1*}_i) - p(\beta^{1*}_i, e^{1*}_i))$$

Because the mechanism selects the allocation that maximizes social surplus, $\beta_i^{2*} - \beta_i^2 < \beta_i^{1*} - \beta_i^1$ holds. Therefore, we obtain the sufficient condition (7). □

The sufficient condition (7) means that if contractor agents are more competitive with one another for providing services for a small bundle of goods than for providing services for a large bundle of goods, this condition is likely to be satisfied, namely, contractor agents report their true value of β_i. A further analysis of our mechanism in the multiple goods case is one of our future works.

6 Concluding remarks

This paper developed a new mechanism to determine the allocation of goods and calculate a contract to solve the incentive problem in file-sharing systems or content delivery services in peer-to-peer networks. Although these services offer new opportunities for trading digital goods such as software, audio/video content, and information, some problems caused by the self-interested nature of agents have been reported, and these problems decrease the advantages of such systems. Furthermore, solving these problems is difficult because the system designer cannot observe each agent's effort level as well as its cost of providing the services.

To solve the problem, we proposed a new mechanism that auctions contracts. More specifically, the mechanism first finds an efficient allocation of the goods and then calculates a contract based on the result of the auction. By analyzing the mechanism through game theory, we showed that the mechanism guarantees that each agent reveals its true information.

In this paper, we assume that the contractee agent cannot observe a contractor agent's technology level and effort level but can observe the result of service provision. The result of service provision is obtained from users' reports. Because there may be observation error, the contractee agent may fail to pay an appropriate reward to contractor agents, which discourages contractor agents from signing the contract. An examination of this problem is one of our future works.

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References

[1] Parameswaran, M., Susarla, A. and Whinston, A. B.: P2P Networking: An Information-Sharing Alternative, *IEEE Computer*, Vol. 34, No. 7, pp. 31–38 (2001).

[2] Sandholm, T. W.: Limitation of the Vickrey Auction in Computational Multiagent Systems, in *Proceedings of the Second International Conference on Multi-Agent Systems (ICMAS-96)*, pp. 299–306 (1996).

[3] Wurman, P. R., Wellman, M. P. and Walsh, W. E.: The Michigan Internet AuctionBot: A configurable auction server for human and software agents, in *Proceeding of the Second International Conference on Autonomous Agents (Agents-98)*, pp. 301–308 (1998).

[4] Yokoo, M., Sakurai, Y. and Matsubara, S.: Robust Combinatorial Auction Protocol against False-name Bids, *Artificial Intelligence Journal*, Vol. 130, No. 2, pp. 167–181 (2001).

[5] Salanié, B.: *The Economics of Contracts*, MIT Press (1997).

[6] Laffont, J.-J. and Tirole, J.: Auctioning Incentive Contracts, *Journal of Political Economy*, Vol. 95, No. 5, pp. 921–937 (1987).

[7] Smith, R. G.: The Contract Net Protocol: High-Level Communication adn Control in a Distributed Problem Solver, *IEEE Transactions on Computers*, Vol. 29, No. 12, pp. 1104–1113 (1980).

[8] Varian, H. R.: Economic Mechanism Design for Computerized Agents, in *First Usenix Workshop on Electronic Commerce* (1995).