Cooperative Virtual Machine Management for Multi-Organization Cloud Computing Environment

Dusit Niyato
School of Computer Engineering
Nanyang Technological University (NTU)
Singapore
dniyato@ntu.edu.sg

Kun Zhu
School of Computer Engineering
Nanyang Technological University (NTU)
Singapore
zhuk0001@e.ntu.edu.sg

Ping Wang
School of Computer Engineering
Nanyang Technological University (NTU)
Singapore
wangping@ntu.edu.sg

ABSTRACT

In cloud computing, organizations can form cooperation to share the available resource to reduce the cost. This is referred to as the multi-organization cloud computing environment. In this paper, we address the issues of virtual machine management and cooperation formation in such an environment. First, for the cooperative organizations, an optimization model is formulated and solved for the optimal virtual machine allocation so that the total cost is minimized. Then, the cost management based on cooperative game theory is applied to obtain the fair share of the cost. Second, the cooperation formation among organizations is analyzed using the network game. With the dynamic cooperation formation, the stable cooperation structure is obtained. Both cooperative virtual machine management and cooperation formation are intertwined, in which the proposed optimization and game models can be used to obtain the solution of the rational organizations to minimize their own costs.

Keywords

Cloud computing, virtual machine, game theory

1. INTRODUCTION

Cloud computing has been emerged to be a promising solution for saving cost and generating more revenue for IT firms. Cloud computing can be considered as a large-scale distributed computing which is motivated by the economy of scale. As a result, cloud computing will be a dynamically-scalable pool of resources (e.g., computing power, storage, platform, and service) which are accessible by the users through the Internet [1]. Therefore, to achieve the advantage of cloud computing, one approach is to consolidate the computing service and create a resource pool which can be accessed by multiple organizations. This is referred to as multi-organization cloud computing environment which can be realized efficiently using the virtualization technology. In such an environment, the computing resource in private cloud (i.e., internal data center) and the service in public cloud (i.e., from service provider) can be shared so as to reduce the total cost due to the increasing resource and service utilization. In multi-organization cloud computing environment, the virtual machine (VM) management will be the key component to allocate VMs to the private cloud, to outsource to public cloud, or to migrate to other data centers. More importantly, it is of interest for the organizations to determine whether they should form the cooperation or not. This will be driven by their costs which should be managed in a fair manner. Optimization and game theory will be the appropriate mathematical tools to analyze this situation.

In this paper, we introduce the cooperative VM management with VM allocation and cost management. First, the optimization model of VM allocation is formulated and solved to obtain the optimal decisions of all cooperative organizations. This optimization considers the VM hosting and migration for private and public cloud over multiple periods. Then, the cost management is introduced based on the cooperative game to obtain the fair division of total cost. The core solution and Shapley value are considered to be the solutions. Then, we analyze the cooperation formation among organizations in this multi-organization cloud computing environment. When the organizations are rational to minimize their own costs, they may choose to cooperate with the selected organizations and implement the cooperative VM management. The dynamics of cooperation formation is studied in the context of the network game. The stable cooperation structure is obtained as the solution which is also the Nash equilibrium of the self-interested organizations. The proposed VM management and the cooperation formation analysis will be useful for the cloud users especially from the economic perspective.

Note that this paper considers different scenarios and extends the work in [2] where the cooperative game is also used to analyze the resource and revenue sharing in cloud computing. The differences between [2] and this paper are as follows: First, in [2], the organizations form a resource pool and offer service as a public cloud to cloud users. Second, [2] considered the demand in a single period instead of multiple periods as in this paper. Third, in [2], only the group of cooperative organizations was considered and the structure of cooperation was not analyzed.

The rest of this paper is organized as follows. Related

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works are reviewed in Section 2. Section 3 describes the system model and assumptions. Section 4 presents the cooperative virtual machine management which is composed of virtual machine allocation and cost management. Section 5 presents the analysis of cooperation formation among organizations to minimize their individual costs. Section 6 presents the performance evaluation results. The paper is summarized in Section 7.

2. RELATED WORK

Cooperation is one of the important concepts to improve the utilization of the resource usage in distributed system. In [3], the computational grid was designed with a distributed resource management scheme. With this scheme, the rational agents for managing the server farm were introduced and they can form the cooperation to share available resource. The automated multiparty negotiation algorithm was used by these agents which are motivated by the economic value (e.g., revenue) of the cooperation. Similarly, the cooperation formation algorithm for the agent-based resource management architecture in computational grid was introduced in [4]. In this case, the cooperation is formed to share the resource to process the computing tasks from multiple computing grids so that the cost is minimized. The concept of virtual organization in computational grid was introduced in [5]. With virtual organization, the available resource in different computing grids can be shared among self-organized and self-interested providers. As a result, their profit can be maximized. This formation was modeled as a game to analyze the structure of formation. In [6], the agent-based service composition scheme was developed. This scheme takes the fact of decentralized decision making, limited knowledge, and rationality of agents to cooperate into account. In [7], the cooperative task scheduling was introduced. It was shown that it is always possible to obtain collaborative solution of the self-interested agents which can improve the global system performance.

Game theory has been applied to study different issues in utility computing (e.g., grid and cloud computing) [8, 9, 10, 11, 12]. For example, in [8], a scheduling algorithm to guarantee quality-of-service (QoS) constrains in an open cloud computing framework was modeled as a game. The assignment of tasks to the available resources was obtained from Nash equilibrium. In [9], the task allocation for computational grid was formulated as the cooperative game. The objective is to minimize the energy consumption with the constraint on processing deadline and architectural requirement. In [13], the agreement settlement among internet service provider (ISP) was studied using cooperative game theory. The Shapley value is applied for the fair profit sharing. The proposed profit sharing can motivate any selfish ISP to apply the routing and connection management so that the Nash equilibrium among all ISPs can be achieved.

However, none of the works in the literature considered the cooperative virtual machine management from the game theoretic perspective. Also, dynamic cooperation formation was ignored in the multi-organization cloud computing environment.

3. SYSTEM MODEL

3.1 Cloud Computing Architecture

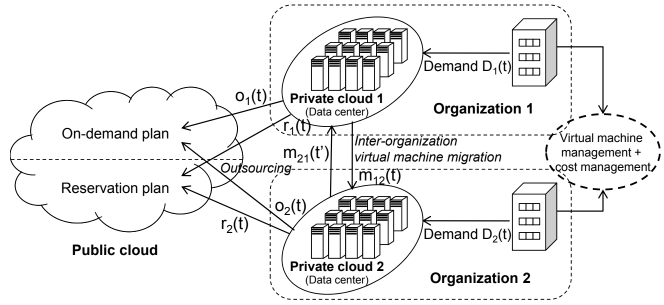

Figure 1: Multi-organization cloud computing environment and virtual machine management.

Cloud computing environment with public cloud service (i.e., virtual machine (VM) hosting) and private cloud (i.e., internal data center) is considered. There are multiple organizations in this cloud computing environment. The set of organizations is denoted by $\mathcal{I} = \{1, \ldots, I\}$ where I is the maximum number of organizations. The VM allocation is performed over T periods, and each period has a fixed time interval (e.g., one day). Without loss of generality, organization $i \in \mathcal{I}$ has a private cloud infrastructure (i.e., data center) with a set of physical machines able to accommodate $V_i(t)$ VMs in period $t \in \{1, \ldots, T\}$ (i.e., internal capacity of organization i). Organization i has a computing demand defined as the number of required VMs denoted by $D_i(t)$. The cost of hosting VM in private cloud (e.g., power consumption cost) of organization i at period t is denoted by $H_i(t)$ \$ per VM per period. Fig. 1 shows the example of a cloud computing environment under consideration with two organizations.

If the private cloud cannot host all demand, the organization can outsource VMs to the service provider in public cloud. Service provider supports two subscription plans for VM hosting, i.e., reservation and on-demand. Reservation plan can be bought and it will be available for $\tau \geq 1$ periods. $r_i(t)$ denotes the capacity (i.e., number of reserved VMs) bought in reservation plan in period t. In this case, organization i can outsource $r_i(t)$ VMs to service provider in public cloud in periods $t, t+1, \ldots, t+\tau-1$. In contrast, on-demand plan can be bought instantaneously, and it will be available only for that period. $o_i(t)$ denotes the capacity bought in period t in which organization i can outsource $o_i(t)$ VMs to service provider to be hosted in on-demand plan only in period t. Service fees of reservation and on-demand plans charged by service provider to the organization (i.e., costs of organization) are denoted by $F_{\mathrm{rs}}(t)$ and $F_{\mathrm{od}}(t)$ \$ per VM per period, respectively. Generally, the service fee of reservation plan per period is cheaper than that of on-demand plan (i.e., $F_{\mathrm{rs}}(t) < F_{\mathrm{od}}(t)$), since the service is reserved in advance for multiple periods (e.g., similar to the whole sale). In addition, it can be assumed that $H_i(t) < F_{\mathrm{rs}}(t) < F_{\mathrm{od}}(t)$.

3.2 Cooperative Virtual Machine Management

Organizations can establish cooperation for virtual machine hosting for periods $1, \ldots, T$. With the cooperation, organizations can share their available resource of hosting VM and agree to perform the cooperative virtual machine management. The cooperation is denoted by $\theta = (i, j)$ where organizations i and j cooperate. The cooperation is symmetric, and, hence, $(i, j) = (j, i)$. Given all organizations in set $\mathcal{I}$, the set of cooperation (i.e., cooperation structure) is denoted by $\zeta \subseteq \mathcal{O}$ where $\mathcal{O}$ is a set of all possible cooperation. For example, with 3 organizations (i.e., $\mathcal{I} = \{1, 2, 3\}$), $\mathcal{O} = \{(1, 2), (1, 3), (2, 3)\}$. If organizations 1 and 2 cooperate, the cooperation structure can be expressed as $\zeta = \{(1, 2)\}$. Given the cooperation structure ζ, a set of cooperative organizations is denoted by $\mathcal{I}_\zeta = \{i, j|\theta = (i, j) \in \zeta\}$.

With cooperation $\theta = (i, j)$, VMs from organization i can be migrated and hosted within the capacity of organization j and vice versa. This VM migration can be performed when the instantaneously peak demand occurs in which the available capacity (i.e., private cloud, subscribed reservation and on-demand plans) of one organization is not enough to host all required VMs and some VMs will be "spilled over" to other organizations with low demands. The number of migrated VMs from organization j to i in period t is denoted by $m_{j,i}(t)$. The cost incurred due to the VM migration (e.g., due to network bandwidth used for migration) from organization j to i is denoted by $G_{j,i}(t)$, where organization j will account for this cost. It is assumed that $G_{j,i}(t) < H_i(t) < G_{j,i}(t) + H_i(t) < F_{\mathrm{rs}}(t) < F_{\mathrm{od}}(t)$.

Organizations with cooperation will perform VM hosting (i.e., host in private cloud or public cloud, or migrate to other organizations) based on the cooperative VM management to achieve the lowest cost. These cooperative organizations can further participate in the cost management in which the total cost is divided among organizations in a fair manner. In the next section, the optimization model will be formulated for the VM allocation and cooperative game will be applied for the cost management.

4. COOPERATIVE VIRTUAL MACHINE MANAGEMENT

In this section, the cooperative virtual machine (VM) management is presented for a given set of cooperative organizations $\mathcal{I}_\zeta \subseteq \mathcal{I}$. Note that for $\zeta = \emptyset$ (i.e., none of organization cooperates), $\mathcal{I}_\zeta = \{i\}$. Cooperative VM management is composed of VM allocation and cost management.

4.1 Virtual Machine Allocation

VM allocation is used to determine the number of VMs to be hosted in private cloud and in public cloud using reservation and on-demand plans, and the number of VMs to be migrated to other organizations. The objective of all cooperative organizations is to minimize the cost while meeting the demand requirements. The optimization model of the VM allocation can be formulated as in (1)-(5), where $v_i(t)$ is the number of VMs to be hosted in private cloud of organization i in period t. The objective in (1) is to minimize the cost of all cooperative organizations within cooperation structure ζ for all periods $1, \dots, T$ due to hosting VMs in private cloud (i.e., $v_i(t)H_i(t)$), migrating VMs among organizations (i.e., $\sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{j,i}(t)G_{j,i}(t)$), buying reservation plan (i.e., $r_i(t)F_{\mathrm{rs}}(t)$) and on-demand plan (i.e., $o_i(t)F_{\mathrm{od}}(t)$) from service provider in public could. Constraint in (2) ensures that the number of VMs to be hosted in private cloud does not exceed the capacity. Constraint in (3) ensures that the demand will be satisfied. Note that the term $\sum_{t'=\max(1,t-\tau+1)}^{t} r_i(t')$ indicates the total available capacity of reservation plan which is reserved in advance. Constraint in (5) indicates that the VM can be migrated only among organizations with cooperation $\theta = (i, j) \in \zeta$. Since the optimization model defined in (1)-(5) is the linear programming, the standard method can be used to obtain the optimal solutions. Then, given the optimal solutions $v_i^*(t)$, $r_i^*(t)$, $o_i^*(t)$, and $m_{i,j}^*(t)$, the minimum cost defines the value of cooperation, i.e., $v(\mathcal{I}_\zeta)$. This value of cooperation will be used in the cost management and the detail of which will be presented later in this paper.

The individual cost of cooperative organization i can be obtained from

$$C_i^{\mathrm{ind}} = \sum_{t=1}^{T}(v_i^*(t)H_i(t) + \sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{i,j}^*(t)G_{i,j}(t) + r_i^*(t)F_{\mathrm{rs}}(t) + o_i^*(t)F_{\mathrm{od}}(t)). \quad (6)$$

In this case, organization i has to account for the migration cost of its emigrated VMs (i.e., $\sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{i,j}^*G_{i,j}(t)$), and the cost of outsourced VMs to public cloud (i.e., $r_i^*(t)F_{\mathrm{rs}}(t) + o_i^*(t)F_{\mathrm{od}}(t)$).

4.2 Cost Management

The cost management is introduced to divide the total cost of cooperative organizations in a fair manner. Two concepts of the fair cost management are adopted from the cooperative game theory, i.e., the core solution and Shapley value [14].

4.2.1 The Core Solution

Definition 1. The core solution of the cooperative game of cost management is defined as follows [15]:

$$\mathcal{C} = \left\{ \vec{\mathbf{c}} \in \Re^{|\mathcal{I}_\zeta|} \middle| \sum_{i\in\mathcal{I}_\zeta} c_i = v(\mathcal{I}_\zeta), \sum_{i\in\mathcal{S}} c_i \le v(\mathcal{S}), \forall \mathcal{S} \subseteq \mathcal{I}_\zeta \right\}, \quad (7)$$

where $\vec{\mathbf{c}} = \left[c_1, \dots, c_i, \dots, c_{|\mathcal{I}_\zeta|}\right]^T$ is a vector of costs of cooperative organizations.

Two important properties of the core solution making it suitable for the cost management in cooperative VM management are the efficiency and rationality. For the efficiency, the cost of all cooperative organizations will be equal to the value of cooperation, i.e., $\sum_{i\in\mathcal{I}_\zeta} c_i = v(\mathcal{I}_\zeta)$. That is, all organizations achieve the lowest total cost. For the rationality, the cost of all cooperative organizations must be equal to or less than those of all subgroups of cooperation, i.e., $\sum_{i\in\mathcal{S}} c_i \le v(\mathcal{S})$, $\forall \mathcal{S} \subseteq \mathcal{I}_\zeta$. That is, the organization will not account for the cost higher than that of other alternative cooperation.

To obtain the core solution, the cooperative VM management defined in (1)-(5) can be considered as the linear programming game [15]. First, the optimization model defined in (1)-(5) can be expressed in the matrix form as follows:

$$\max_{\vec{\mathbf{x}}} \quad -\vec{\mathbf{h}}^T\vec{\mathbf{x}}, \quad (8)$$

$$\text{subject to} \quad \mathbf{H}\vec{\mathbf{x}} \le \vec{\mathbf{b}}, \quad (9)$$

$$\vec{\mathbf{x}} \ge \vec{\mathbf{0}}. \quad (10)$$

$\vec{\mathbf{x}} = [\dots, v_i(t), \dots, m_{j,i}(t), \dots, r_i(t), \dots, o_i(t), \dots]^T$ and $\vec{\mathbf{h}} = [\dots, H_i(t), \dots, G_{j,i}(t), \dots, F_{\mathrm{rs}}(t), \dots, F_{\mathrm{od}}(t), \dots]^T$ are the vectors of decision variables and cost coefficients, respectively.

$$v(\mathcal{I}_\zeta) = \min_{v_i(t),r_i(t),o_i(t),m_{i,j}(t)} \quad \sum_{t=1}^{T}\sum_{i\in\mathcal{I}_\zeta}\left(v_i(t)H_i(t) + \sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{j,i}(t)G_{j,i}(t) + r_i(t)F_{\rm rs}(t) + o_i(t)F_{\rm od}(t)\right), \quad (1)$$

$$\text{subject to} \quad v_i(t) \le V_i(t), \quad i\in\mathcal{I}_\zeta, \;\; t=1,\dots,T, \quad (2)$$

$$v_i(t) + \sum_{t'=\max(1,t-\tau+1)}^{t} r_i(t') + o_i(t) + \sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{i,j}(t) - \sum_{j\in\mathcal{I}_\zeta\setminus\{i\}} m_{j,i}(t) \ge D_i(t)$$

$$i\in\mathcal{I}_\zeta, \;\; t=1,\dots,T, \quad (3)$$

$$v_i(t)\ge 0, \;\; r_i(t)\ge 0, \;\; o_i(t)\ge 0, \quad (4)$$

$$\begin{cases} m_{i,j}(t)\ge 0 & \text{for } (i,j)\in\zeta \\ m_{i,j}(t)=0 & \text{for } (i,j)\notin\zeta \end{cases}, \quad (5)$$

$\vec{\mathbf{b}} = [\dots, V_i(t), \dots, -D_i(t), \dots]^T$ is a vector of private cloud's capacity and organization's demand. $\mathbf{H}$ is a matrix of positive/negative ones and zeros corresponding to the constraints defined in (2)-(5). Negative ones in matrix $\mathbf{H}$ and $-D_i(t)$ in $\vec{\mathbf{b}}$ are used to change the inequality constraint from $\ge$ in (3) to $\le$ in (9). Note that the decision variable $m_{i,j}(t)$ for $(i,j)\notin\zeta$ can be omitted from the formulation since its value is always zero. $\vec{\mathbf{0}}$ is a vector of zeros.

Then, the core solution can be obtained by solving the dual problem defined as follows [15]:

$$\vec{\mathbf{y}}^* = \arg\min_{\vec{\mathbf{y}}} \quad \vec{\mathbf{b}}^T\vec{\mathbf{y}}, \quad (11)$$

$$\text{subject to} \quad \mathbf{H}^T\vec{\mathbf{y}} \ge -\vec{\mathbf{h}}, \quad (12)$$

$$\vec{\mathbf{y}} \ge \vec{\mathbf{0}}, \quad (13)$$

where $\vec{\mathbf{y}}$ is a vector of dual variables representing the shadow prices of cooperative organizations at periods $1,\dots,T$. Let $\vec{\mathbf{y}}^*$ be a vector of optimal dual variables. The core solution of cooperative VM management can be obtained from

$$c_i^* = \vec{\mathbf{b}}_i^T\vec{\mathbf{y}}^*, \quad (14)$$

where $\vec{\mathbf{b}}_i$ is a vector with the elements associated with the capacity and demand of organization i only [15]. Let $\vec{\mathbf{c}}^* = \left[c_1^*,\dots,c_i^*,\dots,c_{|\mathcal{I}_\zeta|}^*\right]^T$ denote a vector of solutions of (14), then $\vec{\mathbf{c}}^*\in\mathcal{C}$ [15]. Note that the core solution can be obtained if the optimization model defined in (1)-(5) is feasible.

4.2.2 Shapley Value

Shapley value can be considered as an alternative to the core solution of the fair cost management. Given the value of cooperation structure $v(\cdot)$ obtained from (1), the Shapley value can be obtained as follows [14]:

$$\phi_i(v) = \sum_{\mathcal{S}\subseteq\mathcal{I}_\zeta\setminus\{i\}} \frac{|\mathcal{S}|!(|\mathcal{I}_\zeta|-|\mathcal{S}|-1|)!}{|\mathcal{I}_\zeta|!}(v(\mathcal{S}) - v(\mathcal{S}\cup\{i\})). \quad (15)$$

Shapley value is suitable for the cost management of cooperative VM management due to the efficiency, individual fairness, symmetry, and uniqueness. For efficiency, similar to that of the core solution, the costs of all cooperative organizations must be minimum, i.e., $\sum_{i\in\mathcal{I}_\zeta}\phi_i(v) = v(\mathcal{I}_\zeta)$. For individual fairness, the Shapley value guarantees the cost to be equal to or lower than the value of individual organization, i.e., $\phi_i(v)\le v(\{i\})$ for all $i\in\mathcal{I}_\zeta$. For symmetry, Shapley value is indifferent for the equivalent organizations. Finally, Shapley value is unique solution of any cooperative game which is desirable for the cost management which all cooperative organizations would agree on.

The VM allocation and cost management are performed given that the organizations in $\mathcal{I}_\zeta$ agree to cooperate. However, the important question is: How the organizations will form cooperation which leads to $\mathcal{I}_\zeta$? In the next section, cooperation formation among all organizations in $\mathcal{I}$ will be analyzed.

5. COOPERATION FORMATION

If the organizations are self-interested to minimize their own costs, they can rationally choose to cooperate in virtual machine (VM) management. That is, all organizations in $\mathcal{I}$ can participate and form different cooperation among each other. In this section, the cooperation formation of organizations will be analyzed given the individual cost obtained from VM allocation and cost management.

5.1 Cooperation Model

The cooperation formation of VM management can be modeled as the network game [16] which can be described as follows: The players are organizations whose set is $\mathcal{I}$ for $|\mathcal{I}|\ge 3$. The strategy of each player is to establish the link (i.e., cooperation) with other players. The link between players i and j is denoted by $l_{i,j}$ where $l_{i,j}=1$ if the link is valid, and $l_{i,j}=0$ otherwise. In this case, organizations or players can be considered as the vertices, while cooperation is the link or edge of the undirected graph. The strategy space of player i is defined as $\mathcal{L}_i = \{(\dots,l_{i,j},\dots)|l_{i,j}\in\{0,1\}, j\in\mathcal{I}\setminus\{i\}\}$. The cooperation structure ζ defined in Section 3.2 can be uniquely mapped into this undirected graph. In particular, the link can be defined based on the cooperation structure as follows:

$$l_{i,j} = \begin{cases} 1, & (i,j)\in\zeta, \\ 0, & (i,j)\notin\zeta, \end{cases} \quad (16)$$

and vice versa.

Let π_i denote the cost of organization i obtained from the VM allocation and cost management. $\pi_i = C_i^{\rm ind}$, $\pi_i = c_i^*$, or $\pi_i = \phi_i$ when the individual cost of VM allocation, the core solution, or Shapley value of cost management obtained respectively from (6), (14), and (15) is applied. In other words, the cooperation formation is independent of VM management and can adopt different solution concepts. The Nash equilibrium of the cooperation formation can be defined based on the following condition:

$$\pi_i(\mathbf{l}_i^*, \mathbf{l}_{-i}^*) \leq \pi_i(\mathbf{l}_i, \mathbf{l}_{-i}^*) \qquad \forall i, \tag{17}$$

where $\mathbf{l}_i \in \mathcal{L}_i$ is the strategy of player i, $\mathbf{l}_i^* \in \mathcal{L}_i$ is the Nash equilibrium strategy, and $\mathbf{l}_{-i}^* \in \prod_{j\in\mathcal{I}\setminus\{i\}} \mathcal{L}_j$ is the Nash equilibrium strategy of all players excluding those of player i. In this case, cost $\pi_i(\cdot)$ is defined as the function of strategies of all players.

The stability of the cooperation formation will be analyzed using the dynamic model of Markov chain.

5.2 Dynamics of Cooperation Formation

Organization makes decision of cooperation formation periodically at iteration $k = 1, 2, \ldots$. In this case, the state of the formation is defined as the strategy profile adopted by all organizations. At each iteration, organization randomly decides to evaluate and switch to new strategy. The strategy $\mathbf{l}_i(k)$ of organization i in iteration k is obtained from

$$\mathbf{l}_i(k) \in \arg\min_{\mathbf{l}_i \in \mathcal{L}_i} \pi_i(\mathbf{l}_i, \mathbf{l}_{-i}(k-1)), \tag{18}$$

where $\mathbf{l}_{-i}(k-1)$ is the strategy of all organizations excluding those of organization i in iteration $k-1$. The strategy update defined in (18) is referred to as the *myopic* best response. That is, the organization i chooses the best strategy given the knowledge of strategies of other organizations in the previous iteration. In addition, we assume that the organizations can make mistakes or irrationally switch the strategies with small probability ϵ.

Discrete-time Markov chain is used to model above strategy adaptation of the cooperation formation [16]. The state space of this Markov chain is defined based on all links of all organizations as follows: $\Omega = \prod_{i\in\mathcal{I}} \mathcal{L}_i$, where again it is assumed that $l_{i,j} = l_{j,i}$. Note that strategy $\mathbf{l}_i$ is part of the state $\omega \in \Omega$ where strategy $\mathbf{l}_i$ contains the links of organization i only. The transition probability of this Markov chain can be obtained as follows: First, the current state $\omega = (\ldots, l_{i,j}, \ldots) \in \Omega$ and the next state $\omega' = (\ldots, l'_{i,j}, \ldots) \in \Omega$ are defined where $l_{i,j}$ and $l'_{i,j}$ are the strategies of organizations i and j at the current and next states, respectively. Given the current state ω and the next state ω', the set of organizations whose strategies are changed can be defined as follows:

$$\mathcal{T}_{\omega,\omega'} = \{i | i \in \mathcal{I}, l_{i,j} \neq l'_{i,j}, j \neq i\}. \tag{19}$$

Then, the transition probability from state ω to ω' can be defined as follows:

$$P_{\omega,\omega'} = \lambda^{|\mathcal{T}_{\omega,\omega'}|}(1-\lambda)^{|\mathcal{I}|-|\mathcal{T}_{\omega,\omega'}|} \prod_{i\in\mathcal{T}_{\omega,\omega'}} \beta_i(\omega,\omega'), \tag{20}$$

where λ is a probability of organization to update its strategy in an iteration. $\beta_i(\omega, \omega')$ is the best-reply rule defined as the function of the current and the next states. The best-reply rule can be defined as follows:

$$\beta_i(\omega,\omega') = \begin{cases} 1-\epsilon, & \pi_i(\omega') < \pi_i(\omega), \\ \epsilon, & \text{otherwise}, \end{cases} \tag{21}$$

$\pi_i(\omega)$ is the cost defined as the function of strategies of all players (i.e., state of cooperation formation). The best-reply rule defined in (21) indicates that the player will switch the strategy if it yields lower cost. However, player can occasionally be irrational with small probability ϵ.

It is shown that this Markov chain is aperiodic and irreducible. Therefore, there is unique stationary probability [16] which can be used to determine the stable cooperation formation. Let $\mathbf{P}$ denote the transition probability matrix whose element is $P_{\omega,\omega'}$ defined in (20). The stationary probability p_ω is the probability that at the steady state, the cooperation formation will be at state ω. The stationary probability vector $\vec{\mathbf{p}} = [\ldots, p_\omega, \ldots]^T$ can be obtained by solving the following equations:

$$\vec{\mathbf{p}}^T\mathbf{P} = \vec{\mathbf{p}}^T, \quad \text{and} \quad \vec{\mathbf{p}}^T\vec{\mathbf{1}} = 1, \tag{22}$$

where superscript ^{T} denotes transpose operator, and $\vec{\mathbf{1}}$ is a vector of ones. For $\epsilon \to 0$ (i.e., organizations make less and less irrational decisions), there will be the state $\omega^\dagger$ where $p_{\omega^\dagger} > 0$. This state is stochastically stable [16]. In addition, any stochastically stable state which is also the absorbing state coincides with the Nash equilibrium [16]. At this absorbing state of cooperation formation, none of organizations can switch the strategy to achieve lower cost. To this end, the stochastically stable state can be uniquely mapped into the stochastically stable cooperation structure as follows: $\zeta^\dagger = \{(i,j) | l_{i,j}(\omega^\dagger) = 1\}$, where $l_{i,j}(\omega^\dagger)$ is a component of $\omega^\dagger$.

6. PERFORMANCE EVALUATION

6.1 Parameter Setting

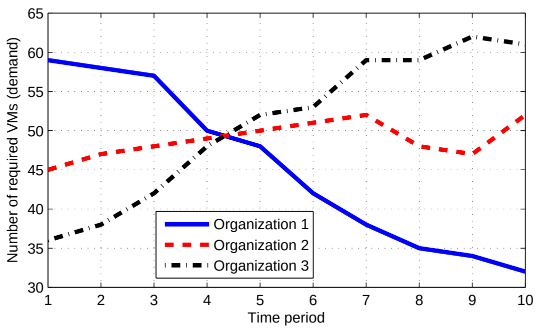

Figure 2: Virtual machine demand over 10 periods.

We consider multi-organization cloud computing environment with 3 organizations. The virtual machine (VM) management is to perform over 10 periods (i.e., 10 days). The demand (i.e., number of required VMs) of each organization is shown in Fig. 2. Each organization has its own private cloud with capacity of 45 VMs. Service provider in public cloud offers the VM hosting in reservation and on-demand plans. The service in reservation plan will be available for 3 periods. The cost of hosting VM in private cloud is 0.1$ per VM per period. Cost of migrating VM is 0.01$ per VM. The service fees of reservation and on-demand plans of public cloud are 0.15 and 0.2$ per VM per period, respectively. The maximum number of VMs to be migrated is equals to the capacity of private cloud. For the cooperation formation, organizations make irrational decision with a probability of 10^{-6}.

For a comparison purpose, we also consider the loosely cooperative VM management based on symmetric sharing scheme. The detail of this scheme is presented in Appendix.

In short, this symmetric sharing scheme allows cooperative organizations to share the capacity for hosting VM. However, the number of VMs migrated to other organizations must be equal to that migrated from other organizations (i.e., number of emigrated VMs equals to number of immigrated VMs) over the periods $1, \ldots, T$.

6.2 Numerical Results

6.2.1 Solution of Virtual Machine Management

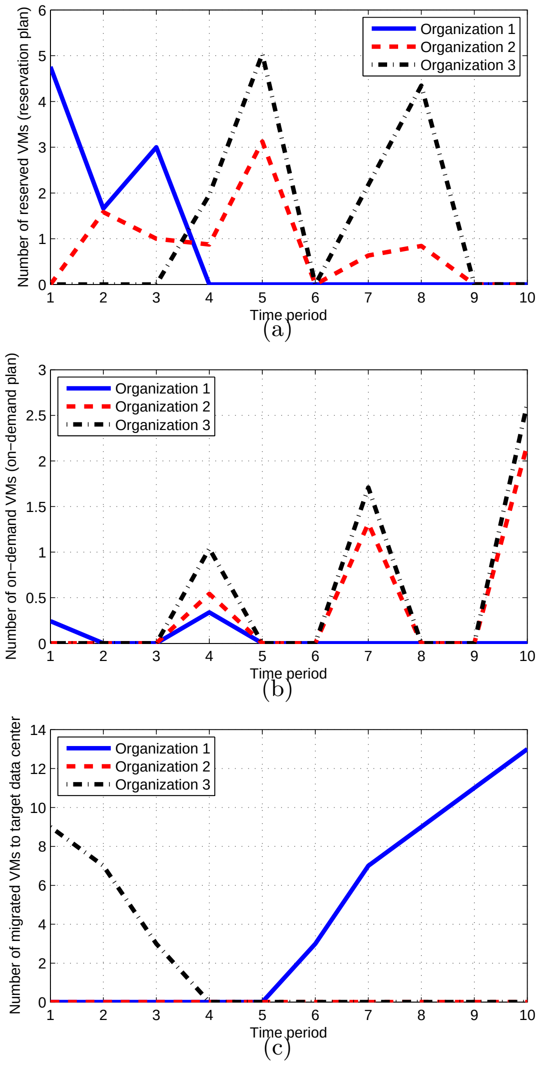

Figure 3: (a) Number of reserved virtual machines, (b) number of on-demand virtual machines, and (c) number of migrated virtual machines.

First, we consider the optimal solution of cooperative VM management when all organizations cooperate. Fig. 3(a) shows the number of reserved VMs (i.e., service capacity of reservation plan) by different organizations. The number of reserved VMs depends on the demand. For example, in periods 1-3, organization 1 reserves some VMs since its demand is large. Similarly, later (i.e., periods 4-8), organization 3 reserves many VMs due to its high demand. Fig. 3(b) shows the number of on-demand VMs (i.e., service capacity of on-demand plan). Since the organization can buy service in the on-demand plan to accommodate instantaneous demand, the VMs are bought in on-demand plan occasionally in some periods only (e.g., in periods 4, 7, and 10). Fig. 3(c) shows the number of migrated VMs from other organizations. Again, the VMs are migrated according to the demand. In the first few periods (i.e., periods 1-3), since the demand of organization 3 is low, other organizations, especially organization 1, migrate many VMs to organization 3. In contrast, later (i.e., periods 6-10), demand of organization 1 becomes small, and, hence, the number of migrated VMs to organization 1 is high. These migrated VMs are mostly from organization 3 whose demand increases during periods 6-10.

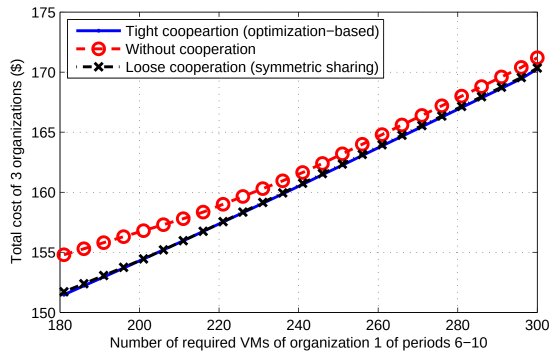

Figure 4: Total cost of all organizations.

Fig. 4 shows the total costs of three organizations with different VM management under varied demand of organization 1 during periods 6-10. As expected, without cooperation, the total cost is the highest, since the available resource (i.e., private cloud and reservation plan) cannot be shared among organizations. The symmetric sharing scheme (i.e., loose cooperation) can reduce the total cost. However, the tight cooperation (i.e., optimization-based) can achieve the optimal solution in which the total cost of all organizations is the lowest.

Based on the results in Figs. 3 and 4, we observe that the proposed cooperative VM management can achieve lower cost than that without cooperation. Since the VMs can be migrated from high demand to low demand organization dynamically, the computing resource in private cloud and service of reservation plan in public cloud can achieve higher utilization,.

6.2.2 Impact of Demand to Cost

Next, we investigate the impact of demand of one organization (i.e., organization 1) when all organizations cooperate. The number of reserved VMs, on-demand VMs, and migrated VMs are shown in Figs. 5(a), (b), and (c), respectively. As expected, as the demand of organization 1 increases, the number of reserved VMs of organizations increases. However, the reserved VMs of organizations 2 and 3 increase and become constant after demand of 260 VMs. Only that of organization 1 keeps increasing. This is due to the fact that there is the cost of VM migration. Therefore, the organizations 2 and 3 whose demands are constant will not be affected by the increasing demand of organization 1, since for organization 1 it is cheaper to reserve VMs from service provider in public cloud directly than to migrate them to other organizations. In Fig. 5(b), the number of on-demand VMs of organizations 2 and 3 are not significantly affected by the increase of demand of organization 1. Note that although the demand of organization 1 increases, the number of on-demand VMs of organization 1 remains zero since the service fee of on-demand plan is higher than that of reservation plan, and organization 1 will reserve more VMs from reservation plan instead (Fig. 5(a)). As expected, in Fig. 5(c), the number of VMs migrated to organization 1 decreases as the demand in periods 6-10 increases. Again, the number of VMs migrated to organizations 2 and 3 are slightly affected by the increasing demand of organization 1.

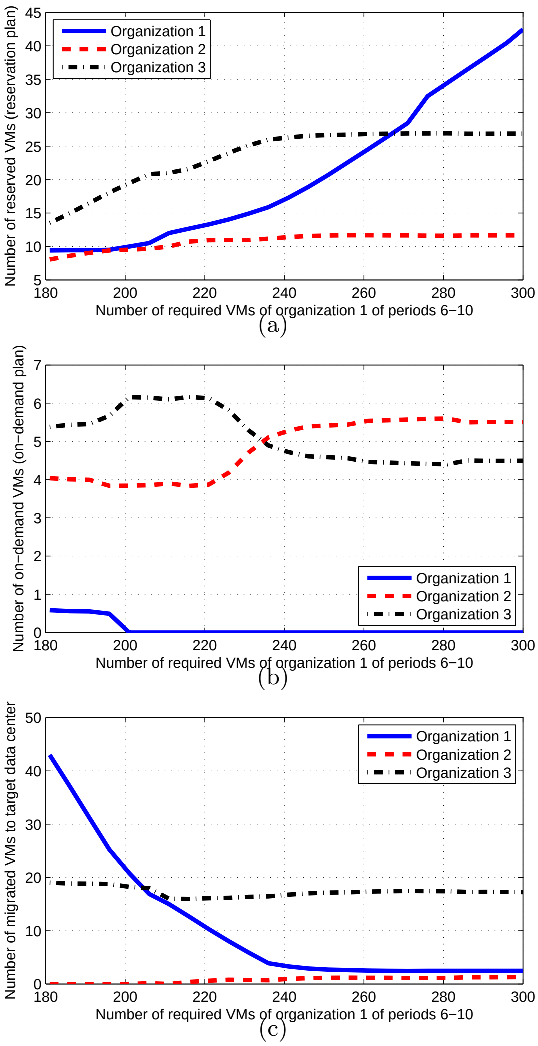

Figure 5: With cooperative virtual machine management, (a) the number of reserved virtual machines, (b) the number of on-demand virtual machines, and (c) the number of migrated virtual machines under varied demand of organization 1 during periods 6-10.

Then, we analyze the effect of cost management. Figs. 6(a) and (b) show the costs of cooperative organizations without and with cost management, respectively. We observe that without cost management, the costs of organizations 2 and 3 can be affected by the increase in demand of organization 1. It is possible that the costs incurred to organizations 2 and 3 become unfair. In particular, the cost from cooperation is higher than that without cooperation although the demand of organizations 2 and 3 remain constant. As a result, these organizations 2 and 3 may not form the cooperation. The cost management is introduced to divide the cost fairly. Consequently, as shown in Fig. 6(b), the costs of organizations 2 and 3 are only slightly affected by the demand of organization 1. More importantly, their costs do not exceed those without cooperation. Therefore, the cooperation can be maintained among them. Note that Fig. 6(b) shows the costs from the core solution. However, the Shapley value and the symmetric sharing scheme yield the similar results and they are omitted for brevity of the paper.

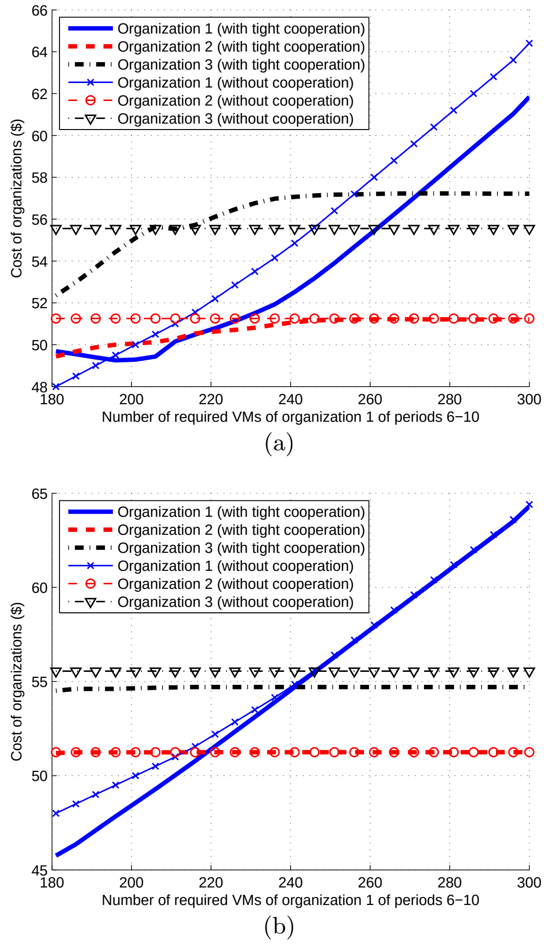

Figure 6: Cost of each organization (a) without cost management (i.e., individual cost), and (b) with cost management (i.e., the core solution) under varied demand of organization 1 during periods 6-10.

6.2.3 Impact of Cost of Virtual Machine Migration

Fig. 7 shows the total number of reserved VMs, total number of on-demand VMs, and total number of migrated VMs of all organizations under different cost of VM migration. As expected, as the VM migration cost increases, the organizations become reluctant to migrate the VMs, and, hence, the number of migrated VMs decreases. Alternatively, organizations prefer to reserve and buy on-demand VMs from public cloud. Note that the similar trend is observed when the service fee of reservation or on-demand plan increases.

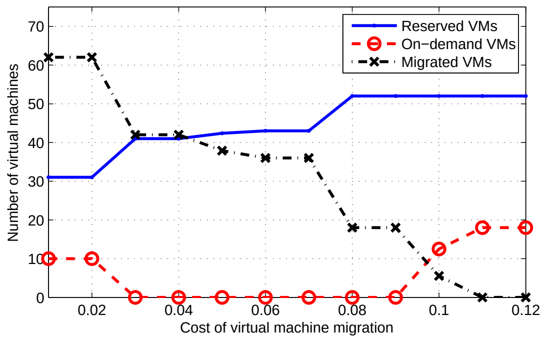

Figure 7: Reserved, on-demand, and migrated virtual machines under different cost of virtual machine migration.

6.2.4 *Cooperation Formation*

Then, the cooperation formation is investigated. The cost matrices from the cooperation with cost management based on the core solution and Shapley value are shown in Tables 1 and 2. Given the cooperation and cost management among organizations, different cooperation structures can be stable. For example, with the core solution, ζ_3, ζ_6, and ζ_8 are stable since their stationary probabilities are greater than zero. In this case, ζ_3 is stable since organizations 1 and 3 can achieve the lowest cost regardless of organization 2, while with ζ_6 and ζ_8, all organizations can achieve the lowest cost. If the cooperation formation reaches any of these structures, none of organizations can reduce their costs without incurring higher cost to other organizations. Therefore, these cooperation structures are stable. We observe the similar effect for the cost management based on Shapley value. Although in the case of Table 1, both the core solution and Shapley value yield the same set of stable cooperation structures, it may not be always the same for other cases. This is shown in Table 2 in which the demand of organization during periods 1-6 increases. The cost management based on the core solution and Shapley value yields different sets of stable cooperation structures. With the complex interaction among organizations and a variety of factors, the analysis of the cooperation formation will be useful to determine which cooperation should be formed by the organizations so that none of them want to deviate.

7. SUMMARY

In cloud computing, organizations can cooperate to share the computing resources so that their costs are minimized. Virtualization technology can be adopted to facilitate this sharing. In this paper, we have introduced the cooperative virtual machine management to allocate virtual machines of each organization to the available resources. Three types of resources have been considered, i.e., private cloud, reservation and on-demand plans of the service provider in public cloud. We have formulated the optimization model to obtain the optimal virtual machine allocation. Also, the cost management for cooperative organizations based on the core solution and Shapley value of cooperation has been proposed. Then, based on the cooperative virtual machine management, we have studied the cooperation formation of organizations. The network game approach has been adopted for the analysis. It is found that the stable cooperation formation which is the Nash equilibrium of the rational organization can be obtained from Markov chain model. The numerical studies have shown that with the virtual machine migration, the computing resource can be efficiently shared which results in lower costs. For the future work, the stochastic nature of demand will be considered.

APPENDIX

Loosely Cooperative Virtual Machine Management

We also consider the loosely cooperative virtual machine management with the symmetric sharing scheme. In this scheme, the organizations establish cooperation to share the capacity and allow VM migration. However, in periods $1, \dots, T$ the number of VMs migrated from any organization must be equal to the number of VMs migrated to this organization. This symmetric sharing scheme ensures that the cooperation will be fair, since all organizations will host the same number of VMs from other organizations as that they migrate to. The symmetric sharing scheme is based on the similar optimization formulation defined in (1)-(5). However, the following constraint is added:

$$\sum_{t=1}^{T} \sum_{j \in \mathcal{I}_\zeta \setminus \{i\}} m_{j,i}(t) = \sum_{t=1}^{T} \sum_{j \in \mathcal{I}_\zeta \setminus \{i\}} m_{i,j}(t), \qquad (23)$$

where $\mathcal{I}_\zeta$ is a set of (loosely) cooperative organizations. The optimal solutions of optimization model with objective function as defined in (1) with constraints defined in (2)-(5), and (23) are $v_i^\star(t)$, $r_i^\star(t)$, $o_i^\star(t)$, and $m_{i,j}^\star(t)$. The individual cost from symmetric sharing scheme denoted by C_i^{sym} can be obtained similar to that in (6).

Acknowledgment

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A. REFERENCES

[1] I. Foster, Y. Zhao, I. Raicu, and S. Lu, “Cloud computing and grid computing 360-degree compared”, in *Proceedings of Grid Computing Environments Workshop (GCE)*, pp. 1-10, November 2008.

[2] D. Niyato and A. V. Vasilakos, “Resource and revenue sharing with coalition formation of cloud providers: Game theoretic approach,” submitted.

[3] L. He and T. R. Ioerger, “Forming resource-sharing coalitions: a distributed resource allocation mechanism for self-interested agents in computational grids,” in

Table 1: Cost matrix for cooperation formation with total demand of 181 virtual machines for organization 1 during periods 1-6.

The core solution				
Cooperation structure	*Organization 1*	*Organization 2*	*Organization 3*	*Stationary Probability*
$\zeta_1 = \emptyset$	48	51.25	55.55	0
$\zeta_2 = \{(1,2)\}$	47.32	50.57	55.55	0
$\zeta_3^\dagger = \{(1,3)\}$	46.37	51.25	53.92	0.40609
$\zeta_4 = \{(2,3)\}$	48	51.2	55.5	0
$\zeta_5 = \{(1,2),(2,3)\}$	46.28333	51.11333	54.46333	0
$\zeta_6^\dagger = \{(1,2),(1,3)\}$	46.15333	50.98333	54.33333	0.29695
$\zeta_7 = \{(1,3),(2,3)\}$	46.9	50.15	54.45	0
$\zeta_8^\dagger = \{(1,2),(1,3),(2,3)\}$	46.15333	50.98333	54.33333	0.29695
The Shapley value				
Cooperation structure	*Organization 1*	*Organization 2*	*Organization 3*	*Stationary Probability*
$\zeta_1 = \emptyset$	48	51.25	55.55	0
$\zeta_2 = \{(1,2)\}$	47.85047	50.03953	55.55	0
$\zeta_3^\dagger = \{(1,3)\}$	45.88337	51.25	54.40663	0.59232
$\zeta_4 = \{(2,3)\}$	48	51.16866	55.53134	0
$\zeta_5 = \{(1,2),(2,3)\}$	46.08337	51.02904	54.74759	0
$\zeta_6^\dagger = \{(1,2),(1,3)\}$	45.75527	51.1997	54.51503	0.21042
$\zeta_7 = \{(1,3),(2,3)\}$	45.76372	51.21751	54.51877	0
$\zeta_8^\dagger = \{(1,2),(1,3),(2,3)\}$	45.75915	51.20024	54.51061	0.19726

Table 2: Cost matrix for cooperation formation with total demand of 256 virtual machines for organization 1 during periods 1-6.

The core solution				
Cooperation structure	*Organization 1*	*Organization 2*	*Organization 3*	*Stationary Probability*
$\zeta_1 = \emptyset$	57.2	51.25	55.55	0
$\zeta_2 = \{(1,2)\}$	57.16	51.21	55.55	0
$\zeta_3^\dagger = \{(1,3)\}$	56.73	51.25	55.08	1
$\zeta_4 = \{(2,3)\}$	57.2	51.2	55.5	0
$\zeta_5 = \{(1,2),(2,3)\}$	56.79333	51.26333	55.13333	0
$\zeta_6 = \{(1,2),(1,3)\}$	56.75	51.22	55.09	0
$\zeta_7 = \{(1,3),(2,3)\}$	56.88667	50.93667	55.23667	0
$\zeta_8 = \{(1,2),(1,3),(2,3)\}$	56.75	51.22	55.09	0
The Shapley value				
Cooperation structure	*Organization 1*	*Organization 2*	*Organization 3*	*Stationary Probability*
$\zeta_1 = \emptyset$	57.2	51.25	55.55	0
$\zeta_2 = \{(1,2)\}$	57.14985	51.22015	55.55	0
$\zeta_3^\dagger = \{(1,3)\}$	57.1	51.25	54.71	0.64515
$\zeta_4 = \{(2,3)\}$	57.2	51.16866	55.53134	0
$\zeta_5^\dagger = \{(1,2),(2,3)\}$	57.08	51.19734	54.91266	0.35485
$\zeta_6 = \{(1,2),(1,3)\}$	57.1	51.25	54.71	0
$\zeta_7 = \{(1,3),(2,3)\}$	57.1	51.25	54.71	0
$\zeta_8 = \{(1,2),(1,3),(2,3)\}$	57.1	51.25	54.71	0

Proceedings of ACM Symposium on Applied Computing (SAC), pp. 84-91, 2005.

[4] G. Yong, Y. Li, W.-M. Zhang, J.-C. Sha, and C.-Y. Wang, "Methods for resource allocation via agent coalition formation in grid computing systems," in *Proceedings of IEEE International Conference on Robotics, Intelligent Systems and Signal Processing*, vol. 1, pp. 295-300, October 2003.

[5] T. E. Carroll and D. Grosu, "Formation of virtual organizations in grids: a game-theoretic approach,"

Concurrency and Computation: Practice and Experience, September 2008.

[6] I. uller, R. Kowalczyk, and P. Braun, “Towards agent-based coalition formation for service composition,” in *Proceedings of the IEEE/WIC/ACM International Conference on Intelligent Agent Technology (IAT)*, pp. 73-80, 2006.

[7] F. Pascual, K. Rzadca, and D. Trystram, “Cooperation in multi-organization scheduling,” in *Proceedings of International Euro-Par Conference*, August 2007.

[8] G. Wei, A. V. Vasilakos, and N. Xiong, “Scheduling parallel cloud computing services: An evolutional game,” in Proceedings of International Conference on Information Science and Engineering (ICISE), pp.376-379, December 2009.

[9] S. U. Khan and I. Ahmad, “A cooperative game theoretical technique for joint optimization of energy consumption and response time in computational grids,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 20, no. 3, pp. 346-360, March 2009.

[10] S. Penmatsa and A. T. Chronopoulos, “Price-based user-optimal job allocation scheme for grid systems,” in *Proceedings of Parallel and Distributed Processing Symposium (IPDPS)*, pp. 8, April 2006,

[11] S. U. Khan and I. Ahmad, “Non-cooperative, semi-cooperative, and cooperative games-based grid resource allocation,” in *Proceedings of Parallel and Distributed Processing Symposium (IPDPS)*, pp. 10, April 2006.

[12] R. Subrata, A. Y. Zomaya, and B. Landfeldt, “Game-theoretic approach for load balancing in computational grids,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 19, no. 1, pp. 66-76, January 2008.

[13] R. T. B. Ma, D. M. Chiu, J. C. S. Lui, V. Misra, and D. Rubenstein, “Internet economics: The use of Shapley value for ISP settlement,” *IEEE/ACM Transactions on Networking*, vol. 18, no. 3, pp. 775-787, June 2010.

[14] B. Peleg and P. Sudholter, *Introduction to the Theory of Cooperative Games*, Springer, November 2010.

[15] G. Owen, “On the core of linear production games,” *Mathematical Programming*, vol. 9, pp. 358-370, 1975.

[16] S. Goyal and F. Vega-Redondo, “Network formation and social coordination,” *Games and Economic Behavior*, vol. 50, no. 2, pp. 178-207, February 2005.