Virtual Machine Trading in Public Clouds

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***Abstract*—By obtaining virtual machines (VMs) from infrastructure providers (InPs) according to the demand in public cloud services, service providers (SPs) can elastically provide network services to users. As the charging methods of VMs, reserved instance (RI) and on-demand instance (ODI) are widely used. For InPs, RI is more desirable than ODI thanks to easiness of estimating long-term revenue, risk aversion of occurring idle VM resources, and reduction of charging cost. In this paper, to improve the ratio of RI in VMs prepared by an InP, we propose VM trading methods in which idle RI of SPs with VM demand falling below the amount of contracted RI are applied to SPs with VM demand exceeding the amount of contracted RI. As the VM trading mechanisms, we investigate two approaches: RI with self-help effort (RISE) and RI with mutual aid (RIMA). Through numerical evaluation using the demand pattern of commercial VoD service, we show that the proposed VM trading methods decrease the number of VMs required for ODI by about 50% to 100% and increase the ratio of RI by about 10% to 70%.**

***Index Terms*—cloud computing, virtual machine, trade**

I. Introduction

Public cloud services, e.g., Amazon EC2, in which users can use computation resources over networks are widely used. In cloud systems, infrastructure providers (InPs) construct and manage datacenters hosting many physical machines (PMs) on which virtual machines (VMs) are set up as well as networks connecting multiple datacenters and users. By purchasing the right to use VMs from InPs, service providers (SPs) offer various services to end users [4][5][17]. InPs also rent virtualized network functions to SPs [20], so we can expect an increase of SPs which provide network services, e.g., video-streaming services, to end users on wide areas [10][11]. Demand of many network services changes cyclically, e.g., over 24 hours or 7 days, based on the life cycle of people [1][7][21][23]. By using public cloud services, SPs can flexibly obtain VMs and network functions according to demand, and various medium or small sized organizations with limited capital are expected to provide various services as SPs.

Typical charging models when SPs obtain VMs from InPs are reserved instance (RI), on-demand instance (ODI), and spot instance (SI) [3]. In RI, SPs can setup and use VMs at any time during a fixed period, e.g., one year or three years, by paying a fixed fee independently of actual usage of VMs. In ODI, SPs can setup and use VMs at any instance during any period, and SPs pay fee based on actual usage. In SI, SPs inform InPs the upper limit of unit price, and VMs are provided to SPs only when the spot price that is dynamically determined by InPs falls below the upper limit. For RI and ODI, the provision of VMs is guaranteed by InPs, whereas it is not guaranteed in SI. Because SPs provide services to end users on business, SPs are required to satisfy the service level agreement (SLA), e.g., delay in service provisioning, network delay, and video quality [12]. To guarantee SLA to users, SPs can consider only RI and ODI as charging model of VMs [12]. In this paper, we consider only VMs obtained by RI or ODI.

InPs own datacenters that consist of PMs and networks. It is in their interest to establish long-term contracts with SPs due to the: (i) simplification in estimating revenue and (ii) their preference for high-utilization of existing resources. Equipment industries need to accurately estimate the long-term revenue to efficiently invest in physical resources. For example, in the case of timeshare resorts, condo developers attempt to maximize the number of units sold to guarantee revenue prior to offering untis for rent. The cost of operating and managing physical resources is almost independent of actual usage, so it is desirable for equipment industries to improve the utilization of physical resources and avoid occurance of idle resources, due to the sunk cost associated with resource acquisition. For example, by selling tickets through agencies, sponsors of events, e.g., music concerts, or airline companies try to avoid occurance of unsold seats. Therefore, as charging model of VMs, RI is superior to ODI for InPs, and improving the ratio of RIs is important for InPs. In Amazon EC2, for example, by setting the average unit price of RI to about 60% in one-year contract and about 40% in three-years contract of that of ODI, Amazon gives motivation to users to select RIs [3].

It is anticipated that SPs will obtain VMs by combining RIs and ODIs so that the total fee is minimized while VM provisioning is guaranteed. In other words, SPs obtain a fixed number of VMs on a long term by RIs, and SPs temporarily get VMs by ODIs when the VM demand exceeds the number of contracted RIs [2][12][22]. In this paper, we call the ratio of VMs provided by RIs among all the VMs provided from InPs as *RI ratio*. If SPs obtain RIs excessively, the number of unused RIs increases. Because the fee of RIs is independent of actual usage of RIs, SPs are motivated to suppress the number of RIs contracted. Therefore, by providing SPs a mechanism to utilize unused RIs, InPs can give SPs motivation to increase the amount of contracted RIs. Hence, in this paper, we propose to apply unused VMs of SPs with VM demand falling below the amount of contracted RIs to SPs with VM demand exceeding the amount of contracted RIs[1]. Through balancing the gap between the VM demand and the amount of contracted RIs among SPs, InPs can expect to improve the RI ratio. The contribution of this paper is summarized as follows.

- We propose the methods enabling InPs to give SPs motivation to increase the RI ratio by trading VMs among SPs without additional fee. The idea of trading VMs

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[1]A shorter version of this manuscript was presented in [14].

among SPs is novel, and InPs can expect to stabilize the long-term revenue by the proposed VM-trading methods.
- We propose two approaches of trading VMs among SPs: (i) RI with self-help effort (RISE) in which the total fee of each SP determined by only the amount of contracted RIs and its own distribution of VM demand, and (ii) RI with mutual aid (RIMA) in which the total fee of each SP depends on the behaviors of other SPs as well as its own behavior. For RISE, we derive the optimum strategies of an InP and SPs in contracts, and we give an algorithm to distribute VMs among SPs which satisfies the max-min fairness in RIMA.
- Through numerical evaluation using the demand pattern of a commercial VoD service, we show that the number of VMs required by an InP to prepare for ODIs decreases about 50% to 100%, the total number of VMs required by an InP to prepare decreases several percent to 20%, and the RI ratio increases about 10% to 70%, by using the proposed VM-trading methods.

In Section II, we summarize the possible ways of InPs to improve the RI ratio and describe the detail of the proposed VM-trading methods in Section III. We show numerical results in Section IV and briefly summarize the related works in Section V. Finally, we conclude this paper in Section VI.

II. Possible Ways Improving RI Ratio

As mentioned in the previous section, improving the RI ratio is desirable for InPs from the viewpoints of (i) simplification in estimating revenue and (ii) their preference for high-utilization of existing resources. In this section, we summarize the possible ways of InPs to improve the RI ratio.

Adjusting price By increasing the difference between the price of ODI and that of RI, InPs can strengthen the motivation for SPs to increase the RI ratio. One approach to increase the price difference is increasing the unit price of ODI while keeping the unit price of RI constant. An extreme case of this approach is setting the unit price of ODI to infinity, that is, offering only RIs without ODIs. However, if other InPs also provide public cloud services, SPs will switch to other InPs to avoid increase of fee. Although the other approach to increase the price difference is decreasing the unit price of RIs while keeping the unit price of ODI constant, the revenue of InPs will decrease. For InPs, improving the RI ratio while sustaining the revenue is desirable.

Smoothing demand InPs can smooth the demand by giving an incentive to shift the starting time of VM provisions for services which are tolerant of timing, e.g., backup service of deposit data of banks [13][15]. By smoothing the demand for VMs, InPs can decrease the number of VMs required to prepare for ODIs and improve the RI ratio. However, there are many services which are strict to timing, e.g., video streaming services, so InPs cannot use this approach widely.

Bundle accommodation Virtual cloud providers which bundle demand of multiple SPs into RIs obtained from InPs have been proposed [24]. In general, the pattern of VM demand is unique on each SP, so VM demand is smoothed by aggregating VM demand of multiple SPs, and the RI ratio will increase. However, although VM provisioning is guaranteed for the aggregated SPs, VM provisioning is not guaranteed for each SP in the bundle. Therefore, when the demand of many SPs in the bundle increases, VMs might not be provided to some SPs in the bundle.

Cloud federation Cloud federation in which cloud providers stabilize their revenue by trading unused VMs among multiple cloud providers has been investigated [9][16][19]. Demand for prepared VMs of InPs are smoothed among InPs, so the number of VMs required by InPs to prepare for ODIs decreases, and the RI ratio will increase. However, cloud federation requires a cooperation among multiple InPs, and it cannot be achieved by just a single InP.

Utilizing unused resources In many cases, the demand of network services and cloud services change periodically [1][7][21][23]. The fee of RIs is independent of actual usage of RIs, so the cost-effectiveness of RIs is degraded if SPs contract many RIs. Therefore, if SPs can obtain reward by giving unused VMs to other SPs which require more VMs than contracted RIs, SPs are motivated to increase the RI ratio. However, SPs have the right to use RIs contracted with InPs at any time during the contracted period in the current charging system of public cloud, so we need an explicit mechanism to temporarily move the right of executing VMs among SPs to realize the VM trading among SPs.

III. VM Trading

In this paper, we focus on the approach of utilizing unused resources to improve the RI ratio, and we propose methods of trading unused RIs among SPs. In this section, we describe the details of the proposed VM trading methods. Table I summarizes the definition of symbols.

A. Assumptions

We assume that a single InP provides VMs of a homogeneous type to SPs by RI or ODI. Time is divided into time slot (TS) with a fixed length, e.g., 60 minutes, and let p denote the normalized unit price of ODI in one TS when the unit price of RI in one TS is unity. The unit price of ODI is larger than that of RI, and we assume $p > 1$. By buying the right to use VMs in RI or ODI, SPs can generate instances on any PMs at any time up to the contracted count during the contract term[2]. We assume that many PMs are provided at the same location, and we ignore the cost of VM migration among PMs.

Let $\boldsymbol{T}$ denote a period consisting T continuous TSs, TS 1 to TS T, and we assume that S SPs provide network services using the public cloud provided by an InP in $\boldsymbol{T}$. Let $\boldsymbol{S}$ denote the set of these S SPs. Moreover, let $g_s(d)$ denote the probability that demand for d VMs is generated from SP $s \in \boldsymbol{S}$ in a TS of $\boldsymbol{T}$, and we have $\sum_{d=0}^{D_s} g_s(d) = 1$ where

[2]Amazon EC2 also provides VMs in the same ways.

TABLE I
DEFINITION OF SYMBOLS.

Symbol	Definition
α_s	Weight of $v_s^p(t)$ against $v_s^c(t)$ in $C_s(t)$
α_s^*, α^*	Optimum α_s maximizing r_s^*, and average α_s^* over all SPs
$C_s(t)$	Contribution function of SP s up to TS t
D_s	Maximum value of d satisfying $g_s(d) > 0$
$d_s(t)$	Number of VMs required by SP s at TS t
F_s	Average normalized fee paid by SP s in each TS of $\boldsymbol{T}$
F	Average F_s over all SPs
$g_s(d)$	Probability distribution of VM demand of SP s
$o_s(t)$	Number of ODIs obtained by SP s up to TS t
p	Normalized unit price of ODI
r_s	Number of RIs contracted by SP s in $\boldsymbol{T}$
r_s^*	Optimum r_s minimizing F_s
R_s	Ratio of demand less than or equal to r_s
R_s^*, R^*	R_s at $r_s = r_s^*$, and average R_s^* over all SPs
$\boldsymbol{S}$, S	Set of SPs, and member count of $\boldsymbol{S}$
$\boldsymbol{S}^+(t)$	Set of SPs with $d_s(t) < r_s$
$\boldsymbol{S}^-(t)$	Set of SPs with $d_s(t) > r_s$
$\boldsymbol{T}$, T	Set of TSs, and member count of $\boldsymbol{T}$
$V^o(t)$	Number of VMs provided to SPs from ODI pool in TS t
$V^+(t)$	Number of VMs provided from $\boldsymbol{S}^+(t)$ to TR
$V^-(t)$	Number of VMs demanded from $\boldsymbol{S}^-(t)$ exceeding RIs
$v_s^c(t)$	Number of VMs provided from TR to SP s up to TS t
$v_s^p(t)$	Number of VMs provided from SP s to TR up to TS t
$\boldsymbol{W}_s^+(t)$	Set of TS τ with $d_s(\tau) < r_s$ in $1 \le \tau \le t$
$\boldsymbol{W}_s^-(t)$	Set of TS τ with $d_s(\tau) > r_s$ in $1 \le \tau \le t$
$x_s(t)$	Number of VMs assigned to SP s from TR in TS t
Z_r	Number of VMs prepared by InP for providing RIs
Z_o	Number of VMs prepared by InP for providing ODIs

D_s is the maximum value of d in SP s. In $\boldsymbol{T}$, we assume that SP s contracts r_s RIs with an InP; in other words, SP s has the right to execute r_s VMs at maximum in all TSs of $\boldsymbol{T}$. We define F_s as the average fee paid by SP s to an InP in each TS of $\boldsymbol{T}$.

B. Optimum Strategy of SP in ROD

We call the existing charging method offering VMs by RI or ODI without VM trading as *ROD* (reserved and on-demand). In ROD, SPs obtain VMs by ODI when the VM demand exceeds r_s, so F_s in ROD is derived by

$$F_s = r_s + p \sum_{d=r_s+1}^{D_s} (d - r_s) g_s(d). \tag{1}$$

We define r_s^* as the optimum r_s for SP s minimizing F_s, and r_s^* is obtained by

$$r_s^* = \underset{0 \le r_s \le D_s}{\arg\min} F_s. \tag{2}$$

SP s has the motivation to set $r_s = r_s^*$.

C. Mechanisms of VM Trading

Let $d_s(t)$ denote the VM demand of SP s in TS t. At the beginning of TS t of $\boldsymbol{T}$, SP s of $\boldsymbol{S}$ informs $d_s(t)$ to an InP. We define $\boldsymbol{S}^+(t)$ and $\boldsymbol{S}^-(t)$ as the set of SPs with $d_s(t) < r_s$ and $d_s(t) > r_s$, respectively. An InP allocates unused VMs of $\boldsymbol{S}^+(t)$ to $\boldsymbol{S}^-(t)$, and we call the place trading VMs between $\boldsymbol{S}^+(t)$ and $\boldsymbol{S}^-(t)$ as the *TR* (trading room) for convenience. We note that the TR is just a concept and does not mean a physical place. SPs of $\boldsymbol{S}^+(t)$ do not receive money for providing VMs to the TR, and SPs of $\boldsymbol{S}^-(t)$ do not pay fee for obtaining VMs from the TR. Let $V^+(t)$ denote the total number of VMs provided from $\boldsymbol{S}^+(t)$ to the TR, and let and $V^-(t)$ denote the total number of VM demand of $\boldsymbol{S}^-(t)$ which are not satisfied by RIs. $V^-(t)$ is obtained by

$$V^-(t) = \sum_{s \in \boldsymbol{S}^-(t)} \Big\{ d_s(t) - r_s \Big\}. \tag{3}$$

On the other hand, $V^+(t)$ is determined by voluntary behavior of SPs of $\boldsymbol{S}^+(t)$. To make SPs of $\boldsymbol{S}^+(t)$ to provide RIs to the TR, an InP needs to provide a mechanism that SP s can receive VMs from the TR without fee in TS t of $d_s(t) > r_s$ as a reward of providing unused RIs to the TR. Therefore, we introduce $C_s(t)$, the contribution function of SP s up to TS t, which is a function of $v_s^p(t)$, the number of VMs provided from SP s to the TR up to TS t, and $v_s^c(t)$, the number of VMs provided from the TR to SP s up to TS t. $C_s(t)$ monotonically increases with increasing $v_s^p(t)$ and monotonically decreases with increasing $v_c^p(t)$. An InP charges $-pC_s(T)$ to SP s at the end of TS T if $C_s(T) < 0$. In other words, we give F_s by

$$F_s = r_s + \frac{p}{T} \Big\{ o_s(T) - \min\Big\{ C_s(T),\ 0 \Big\} \Big\}, \tag{4}$$

where $o_s(t)$ is the total number of ODIs which SP s obtains in TS τ of $1 \le \tau \le t$. In this case, the following proposition is satisfied for $V^+(t)$.

Proposition 1. When F_s is given by (4), $V^+(t)$ is obtained by

$$V^+(t) = \sum_{s \in \boldsymbol{S}^+(t)} \Big\{ r_s - d_s(t) \Big\}. \tag{5}$$

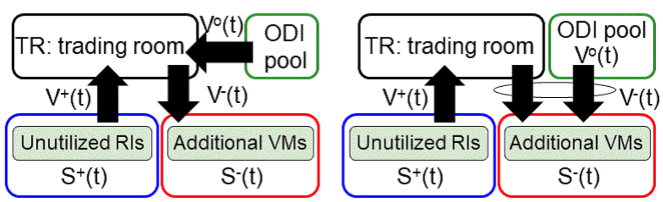
Proof. F_s does not change even if SP s keeps unused RIs without providing them to the TR. On the other hand, with the increase of $v_s^p(t)$, $C_s(t)$ monotonically increases according to the definition of $C_s(t)$, and F_s given by (4) monotonically decreases. Therefore, SP s can minimize F_s by setting $v_s^p(t)$ to the maximum possible value, i.e., the total number of unused RIs up to TS t, $\sum_{1 \le \tau \le t} \{r_s - d_s(\tau)\}$. As a result, $V^+(t)$ is obtained by (5). □

From (4), F_s depends on $C_s(T)$ and $o_s(T)$, and we consider the following two approaches as the method of setting $C_s(T)$ and $o_s(T)$.

RISE (RI with Self-help Effort)

At TS t, VMs are provided from the TR for all the $d_s(t) - r_s$ VM demand which are not satisfied by RIs of SP s of $\boldsymbol{S}^-(t)$. Because SPs do not need to obtain VMs by ODI, F_s is determined by only $C_s(T)$ and r_s. In other words, F_s depends on only $d_s(t)$ and r_s. Therefore, F_s is independent of $d_{s'}(t)$ and $r_{s'}$ of another SP s'. F_s is determined by only behavior of SP s, so RISE is an analogy of the defined contribution plan in which the future benefit of person is determined by its own contribution and investment earning. We can derive r_s^* when $d_s(t)$ and p are given. When $V^+(t) < V^-(t)$, a part of VM demand of $V^-(t)$, $V^o(t) = V^-(t) - V^+(t)$, are not covered by $V^+(t)$ VMs provided by $\boldsymbol{S}^+(t)$. As shown in Fig. 1(a), $V^o(t)$ VMs are provided from the ODI pool to SPs of $\boldsymbol{S}^-(t)$ via the TR without fee.

RIMA (RI with Mutual Aid)
At TS t, VMs less than or equal to $V^+(t)$ are provided from the TR to $\boldsymbol{S}^-(t)$ without fee. Because the unused RIs of $\boldsymbol{S}^+(t)$ are shared among SPs of $\boldsymbol{S}^-(t)$, RIMA is an analogy of public pension fund in which the sum of pension contributions and tax in each year is distributed among the pensioners[3]. When $V^+(t)$ VMs are not enough to satisfy all the $V^-(t)$ demand, SPs need to obtain ODIs for the unsatisfied VM demand as shown in Fig. 1(b). In other words, although VMs are provided from the ODI pool for $V^o(t) = V^-(t) - V^+(t)$ VM demands which are not satisfied by $V^+(t)$ like RISE, these VMs are provided to SPs by ODI without going through the TR. Therefore, SP s needs to pay ODI fee for VM demand exceeding r_s, so F_s depends on $d_{s'}(t)$ and $r_{s'}$ of other SP s' in addition to its own $d_s(t)$ and r_s. Therefore, deriving r_s^* is difficult.



(a) RISE (b) RIMA

Fig. 1. Concept of RISE and RIMA

D. VM Trading on RISE

1) Definition of Contribution Function: In RISE, VMs are provided from the TR to SP s for all $d_s(t) - r_s$ VM demand unsatisfied by RIs, so we have $o_s(t) = 0$ and $v_s^c(t) = \sum_{\tau=1}^{t} \max\{d_s(\tau) - r_s,\, 0\}$. The simplest way to define the contribution function $C_s(t)$ in RISE is setting $C_s(t) = v_s^p(t) - v_s^c(t)$, and we call RISE with this contribution function as *NRISE* (Naive RISE). From Proposition 1, $C_s(t)$ in NRISE is given by

$$C_s(t) = \sum_{\tau=1}^{t} \Big\{ r_s - d_s(\tau) \Big\}, \tag{6}$$

and F_s in NRISE is obtained by

$$\begin{aligned} F_s &= r_s - \frac{p}{T} \min\Big\{ C_s(T),\ 0 \Big\} \\ &= r_s + p \cdot \max\Big\{ \sum_{d=0}^{D_s} (d - r_s) g_s(d), 0 \Big\}. \end{aligned} \tag{7}$$

For r_s^* in NRISE, the following theorem is established.

Theorem 1. In NRISE, r_s^* is determined by only $g_s(d)$.

[3]We assume the public pension system in Japan.

Proof. When r_s is the mean of $g_s(d)$, i.e., $r_s = \overline{g_s} = \sum_{d=0}^{D_s} d g_s(d)$, we have $C_s(T) = \sum_{d=0}^{D_s} (r_s - d) g_s(d) = 0$. $C_s(T)$ monotonically increases as r_s increases, so $F_s = r_s + p \sum_{d=0}^{D_s} (d - r_s) g_s(d)$ when $r_s \le \overline{g_s}$ from (7). We write F_s as $F_s(r_s)$ when we want to explicitly indicate the value of r_s, and we define $\Delta F_s(r_s)$ as $\Delta F_s(r_s) \equiv F_s(r_s) - F_s(r_s - 1)$. When $r_s \le \overline{g_s}$, we have $\Delta F_s(r_s) = -p < 0$, so F_s monotonically decreases as r_s increases. On the other hand, when $r_s > \overline{g_s}$, we have $F_s = r_s$, so F_s monotonically increases with increase of r_s. Therefore, F_s is always minimized when $r_s = \overline{g_s}$, and r_s^* is determined by only $g_s(d)$. □

Therefore, it is difficult for an InP to increase r_s^* and improve the RI ratio through controllable parameters, such as p. Hence, we introduce a parameter α_s taking real number in the range of $0 \le \alpha_s \le 1$, and we give $C_s(t)$ by

$$\begin{aligned} C_s(t) &= \alpha_s \cdot v_s^p(t) - v_s^c(t) \\ &= \alpha_s \sum_{\tau \in \boldsymbol{W}_s^+(t)} \Big\{ r_s - d_s(\tau) \Big\} \\ &\qquad - \sum_{\tau \in \boldsymbol{W}_s^-(t)} \Big\{ d_s(\tau) - r_s \Big\}, \end{aligned} \tag{8}$$

where $\boldsymbol{W}_s^+(t)$ and $\boldsymbol{W}_s^-(t)$ is the set of TS τ in which $d_s(\tau) < r_s$ and $d_s(\tau) > r_s$ in $1 \le \tau \le t$, respectively. By configuring α_s, an InP can expect to increase r_s^* and the RI ratio. We note that ROD and NRISE are special cases of RISE with α_s set to zero and one respectively.

2) Algorithm of VM Trading: In Algorithm 1, we show the procedure of RISE called *PRISE* which is executed by an InP at the beginning of TS t. At the beginning of TS 1, an InP initializes $C_s(0)$ to zero for all SPs, and we assume that SP s of $\boldsymbol{S}$ informs $d_s(t)$ to an InP at the beginning of TS t.

Algorithm 1 PRISE

1: Derives $V^-(t)$ and $V^+(t)$ by (3) and (5)
2: If $V^-(t) > V^+(t)$, applies $V^-(t) - V^+(t)$ VMs to the TR from ODI pool
3: Allocates $d_s(t) - r_s$ VMs from the TR to SP s of $\boldsymbol{S}^-(t)$
4: Updates $C_s(t) = C_s(t-1) + \alpha_s \{r_s - d_s(t)\}$ for SP s of $\boldsymbol{S}^+$, and updates $C_s(t) = C_s(t-1) - \{d_s(t) - r_s\}$ for SP s of $\boldsymbol{S}^-$

3) Optimum Design of r_s and α_s: We define $\gamma(r_s)$ as

$$\gamma(r_s) \equiv \sum_{d=r_s+1}^{D_s} (d - r_s) g_s(d) - \alpha_s \sum_{d=0}^{r_s - 1} (r_s - d) g_s(d). \tag{9}$$

For r_s^*, the optimum r_s for SP s minimizing F_s, and α_s^*, the optimum α_s for an InP maximizing r_s^*, we have the following theorem.

Theorem 2. In RISE, r_s^* is obtained by

$$r_s^* = \begin{cases} r_s^e, & \text{when } 0 \le \alpha_s < \alpha_s^o, \\ r_s^o, & \text{when } \alpha_s^o \le \alpha_s \le 1, \end{cases} \tag{10}$$

where r_s^o is the solution of r_s satisfying $\gamma(r_s) = 0$, and r_s^e is the solution of r_s satisfying $\Delta F_s(r_s) = 0$ in the range of

$0 < r_s \le r_s^o$. Moreover, α_s^o is the solution of α_s satisfying $\Delta F_s(r_s^o) = 0$ when $p \le 1/\sum_{d=r_s^o}^{D_s} g_s(d)$, and $\alpha_s^o = 0$ when $p > 1/\sum_{d=r_s^o}^{D_s} g_s(d)$. Moreover, α_s^* is obtained by

$$\alpha_s^* = \underset{0<\alpha_s\le 1}{\arg\max}\ r_s^*. \tag{11}$$

Proof. From (4) and (8), F_s is given by

$$F_s = r_s + p \cdot \max\Big\{\gamma(r_s),\ 0\Big\}. \tag{12}$$

$\gamma(r_s)$ monotonically increases as r_s increases, and we have

$$\begin{aligned}\gamma(0) &= \sum_{d=1}^{D_s} d g_s(d) > 0,\\ \gamma(D_s) &= -\alpha_s \sum_{d=0}^{D_s-1} (D_s - d) g_s(d) < 0,\end{aligned}$$

so there exists r_s^o satisfying $\gamma(r_s^o) = 0$ in the range of $0 < r_s < D_s$. Next, we consider the condition in which F_s is minimized by separating the range of r_s at r_s^o.

(i) When $0 \le r_s \le r_s^o$:

Because $\gamma(r_s) \ge 0$, we have

$$\begin{aligned}F_s &= r_s + p\gamma(r_s), &(13)\\ \Delta F_s(r_s) &= 1 - p\Big\{\sum_{d=r_s}^{D_s} g_s(d) + \alpha_s \sum_{d=0}^{r_s-1} g_s(d)\Big\}. &(14)\end{aligned}$$

We set $\alpha_s \le 1$, so $\Delta F_s(r_s)$ is a monotonically non-decreasing function of r_s. We have $\Delta F_s(0) = 1 - p\sum_{d=0}^{D_s} g_s(d) = 1 - p$, and $\Delta F_s(0)$ satisfies $\Delta F_s(0) < 0$ because $p > 1$.

When $\alpha_s = 1$, we have $\Delta F_s(r_s^o) = 1 - p < 0$, so $\Delta F_s(r_s^o)$ monotonically decreases with increase of α_s. Now, we define $\Delta F_s(r_s^o)|_{\alpha_s=0}$ as the value of $\Delta F_s(r_s^o)$ when $\alpha_s = 0$, i.e., $\Delta F_s(r_s^o)|_{\alpha_s=0} = 1 - p\sum_{d=r_s^o}^{D_s} g_s(d)$. When $\Delta F_s(r_s^o)|_{\alpha_s=0} \ge 0$, i.e., $p \le 1/\sum_{d=r_s^o}^{D_s} g_s(d)$, there exists α_s^o which is the solution of α_s satisfying $\Delta F_s(r_s^o) = 0$. Therefore, when $0 \le \alpha_s < \alpha_s^o$, we have $\Delta F_s(r_s^o) > 0$, and there exists r_s^e which is the solution of r_s satisfying $\Delta F_s(r_s) = 0$ in the range of $0 < r_s \le r_s^o$ as shown in Fig. 2(a). When $0 \le r_s < r_s^e$, we have $\Delta F_s(r_s) < 0$, and F_s monotonically decreases as r_s increases; whereas when $r_s^e < r_s \le r_s^o$, we have $\Delta F_s(r_s) > 0$, and F_s monotonically increases as r_s increases as shown in Fig. 2(a). Hence, as shown in Fig. 2(b), F_s takes the minimum value at $r_s = r_s^e$.

On the other hand, when $\alpha_s^o \le \alpha_s \le 1$, as shown in Fig. 2(a), we have $\Delta F_s(r_s) \le 0$ in the range of $0 \le r_s \le r_s^o$, and F_s is a monotonically non-increasing function of r_s. Therefore, F_s is minimized when $r_s = r_s^o$. Moreover, when $\Delta F_s(r_s^o)|_{\alpha_s=0} < 0$, we have $\Delta F_s(r_s) \le 0$ in the range of $0 \le r_s \le r_s^o$, so F_s is also a monotonically non-increasing function of r_s, and F_s takes the minimum value at $r_s = r_s^o$.

(ii) When $r_s^o \le r_s \le D_s$:

As $\gamma(r_s) \le 0$, we have $F_s = r_s$ and $\Delta F_s(r_s) = 1$, so F_s monotonically increases as r_s increases, and F_s is minimized when $r_s = r_s^o$.

In sum, r_s^*, the optimum value of r_s for SP s minimizing F_s, is given by (10). Moreover, as α_s^* is the value of α_s maximizing r_s^*, α_s^* is given by (11). □

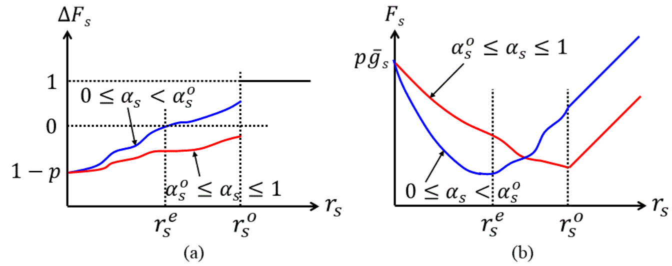


Fig. 2. (a) Relationship between r_s and $\Delta F_s(r_s)$ in RISE, (b) relationship between r_s and F_s in RISE

E. VM Trading on RIMA

1) Definition of Contribution Function: At the beginning of TS t, an InP distributes $V^+(t)$ VMs provided by SPs of $\boldsymbol{S}^+(t)$ to SPs of $\boldsymbol{S}^-(t)$. Let $x_s(t)$ denote the allocation of VMs from the TR to SP s at TS t, and we have $\sum_{s\in\boldsymbol{S}^-} x_s(t) = V^+(t)$. In the same way with NRISE, we set $C_s(t)$ as $C_s(t) = v_s^p(t) - v_s^c(t)$, and $-pC_s(T)$ is charged SP s as ODI fee at the end of $\boldsymbol{T}$. $C_s(t)$ is given by

$$C_s(t) = \sum_{\tau\in\boldsymbol{W}_s^+(t)} \Big\{r_s - d_s(\tau)\Big\} - \sum_{\tau\in\boldsymbol{W}_s^-(t)} x_s(t). \tag{15}$$

When $V^+(t) < V^-(t)$, there exists SPs in $\boldsymbol{S}^-(t)$ in which not all VM demand is satisfied by VMs provided from TR, i.e., $d_s(t) > r_s + x_s(t)$. Like ROD, these SPs obtain $d_s(t) - r_s - x_s(t)$ VMs by ODI, so F_s is given by

$$\begin{aligned}F_s \ &= \ r_s - \frac{p}{T}\min\Big\{C_s(T), 0\Big\}\\ &\quad + \frac{p}{T}\sum_{t\in\boldsymbol{W}_s^-(T)} \max\Big\{d_s(t) - r_s - x_s(t),\ 0\Big\}. \end{aligned}\tag{16}$$

2) Algorithm of VM Trading: Based on the progressive filling algorithm [6], we consider distributing $V^+(t)$ VMs to SPs of $\boldsymbol{S}^-(t)$, and we show PRIMA (procedure of RIMA), the procedure executed by an InP at the beginning of TS t, in Algorithm 2. We note that $x_s(t)$ is not limited to integer and can take positive real number, and $|\boldsymbol{N}|$ stands for the number of members of set $\boldsymbol{N}$. At the beginning of TS 1, an InP initializes $C_s(0)$ to zero for all SPs, and SP s of $\boldsymbol{S}$ informs $d_s(t)$ to an InP at the beginning of TS t.

Algorithm 2 PRIMA

1: Initializes V, the number of VMs which can be allocated to SPs of $\boldsymbol{S}^-(t)$, to $V^+(t)$, initializes $\boldsymbol{M}$, the set of SPs in which VMs have not been completely allocated to VM demand, to $\boldsymbol{S}^-(t)$, and initializes $x_s(t)$ to zero for all SPs

2: Repeats updating $x_s(t) = x_s(t) + 1$, $V = V - |\boldsymbol{N}|$, and $\boldsymbol{N} = \boldsymbol{N} \setminus \{s : x_s(t) = d_s(t) - r_s\}$ for $s \in \boldsymbol{N}$ so long as $V > |\boldsymbol{N}|$

3: If $V \le |\boldsymbol{N}|$, completes the procedure after updating $x_s(t) = x_s(t) + V/|\boldsymbol{N}|$ for $s \in \boldsymbol{N}$, $C_s(t) = C_s(t-1) + \{r_s - d_s(t)\}$ for $s \in \boldsymbol{S}^+(t)$, and $C_s(t) = C_s(t-1) - x_s(t)$ for $s \in \boldsymbol{S}^-(t)$

3) Discussion: An InP is required to satisfy fairness among SPs of $\boldsymbol{S}^-(t)$ which are allocated VMs from the TR. Max-min fairness (MMF) is a well-known concept of fairness, and its definition is given as follows [18].

Definition 1. Let $\boldsymbol{X} \subseteq \mathbb{R}^m$ denote a set of feasible allocation of any resources among m players. A vector $\boldsymbol{x}^0$ is max-min fair on set $\boldsymbol{X}$ if, and only if, $\forall \boldsymbol{x} \in \boldsymbol{X}$, $\exists k \in \{1, \ldots, m\}$, $(x_k > x_k^0) \Rightarrow (\exists j \in \{1, \ldots, m\},\ x_j < x_j^0 \leq x_k^0)$.

The following theorem for $x_s(t)$ is realized by PRIMA.

Theorem 3. The allocation $x_s(t)$ given by PRIMA always satisfies MMF.

Proof. We set the ID of SPs of $\boldsymbol{S}^-(t)$ in ascending order of $d_s(t) - r_s$. In other words, $d_1(t) - r_1 \leq d_2(t) - r_2 \leq \cdots \leq d_M(t) - r_M$, where $M \equiv |\boldsymbol{S}^-(t)|$. $x_s(t)$ takes a value in the range of $0 \leq x_s(t) \leq d_s(t) - r_s$. When $V^+(t) \geq V^-(t)$, $x_s(t) = d_s(t) - r_s$ is satisfied for all the SPs of $\boldsymbol{S}^-(t)$, and there is no room to increase $x_s(t)$, so MMF is obviously satisfied. Therefore, we consider the case of $V^+(t) < V^-(t)$ in which there exists one or more SPs whose VM demand is not fully satisfied by VMs provided from the TR.

PRIMA repeats the procedure allocating one VM to all the SPs with $x_s(t) < d_s(t) - r_s$, so we have $x_s(t) = d_s(t) - r_s$ for $1 \leq s < s_0$, and we have $x_s(t) < d_s(t) - r_s$ and $x_{s_0}(t) = x_{s_0+1}(t) = \ldots = x_M(t)$ for $s_0 \leq s \leq M$, where s_0 is the minimum value of s satisfying $x_s(t) < d_s(t) - r_s$. Therefore, there is room to increase $x_s(t)$ only for SPs of $s \geq s_0$, and we consider increasing $x_{s'}(t)$ for any SP s' of $s \geq s_0$. Because $\sum_{s \in \boldsymbol{S}^-(t)} x_s(t) = V^+(t)$, we need to decrease $x_{s''}$ of any $s'' \in \boldsymbol{S}^-(t)$ to increase $x_{s'}(t)$. On the other hand, $x_1(t) \leq x_2(t) \leq \ldots \leq x_{s_0}(t) = \ldots = x_{s'}(t) = \ldots = x_M(t)$, so we have $x_{s''} \leq x_{s'}$. Therefore, according to definition 1, allocation $x_s(t)$ of PRIMA always satisfies MMF. □

Unlike RISE, F_s depends on $x_s(t)$ at $t \in \boldsymbol{W}_s^-(t)$ in addition to $g_s(d)$ in RIMA as shown in (16). $x_s(t)$ depends on the status of the TR, i.e., the distribution and the change pattern of VM demand of other SPs, so we cannot derive r_s^* in advance. Therefore, it is desirable for an InP to support SPs to set r_s, e.g., proposing r_s^* estimated from the past change pattern of the TR status.

As any SP increases r_s, $V^+(t)$ will increase in some TSs, and $x_s(t)$ of some SPs will also increase. With the increase of $x_s(t)$, the number of ODIs obtained by SPs decreases, and F_s decreases, so RIMA has the *positive externality*, i.e., an increase of r_s by SP s benefits other SPs [8]. In systems with positive externality, all players are motivated to take free ride on other players, and all players try to avoid being free-ridden by other players, so the realized contribution of each player will be smaller than the optimum contribution maximizing the social welfare [8]. Therefore, in RIMA, SP s is motivated to set r_s smaller than the optimum value r_s^*, and RIMA is effective only when an InP has a mechanism to control r_s.

IV. Numerical Evaluation

A. VM Demand

We assume a video delivery service as the network service of SPs, and we use the access log data of PowerInfo VoD system which is a commercial VoD service of China Telecom [23] to set $d_s(t)$, the VM demand of each SP. This log data consists of 20,921,657 requests during 212 days from June 2004 to December 2004. We set the length of TS to 60 minutes and set the length of $\boldsymbol{T}$ to one week, i.e., $T = 7 \times 24 = 168$. We assume that each VM can support 200 sessions simultaneously at maximum, and we set $b(t)$, the base demand at each TS, to the number of streaming sessions of PowerInfo VoD exist in TS t divided by 200. Figure 3(a) plots $b(t)$ from the first day to the seventh day, and we observed a cyclic change pattern with period of a day[4].

The effect of VM trading among SPs depends on the degree of overlapping of peak hours among SPs. Therefore, we select $\Delta_1 \times 24 + \Delta_2$ as the starting TS of VM demand of SP s and set $d_s(t) = b(\Delta_1 \times 24 + \Delta_2 + t)$, where Δ_1 and Δ_2 are random variables taking integer in the range $[0 : 204]$ and $[0 : \delta]$, respectively. δ is a setting parameter taking an integer between zero and 24. Figure 3(b)-(d) shows examples of $d_s(t)$ of six SPs when setting $S = 6$ and δ to 0, 12, or 24. As δ increases, the degree of overlap among SPs in peak hours of VM demand decreases. In the following evaluation, we set $S = 20$, and we evaluate the properties by the means over 1,000 trials with different setting patterns of $d_s(t)$.

We define the RI ratio R_s as the ratio of VM demand satisfying $d \leq r_s$, i.e., $R_s \equiv \sum_{d=0}^{r_s} g_s(d)$. Moreover, let R_s^* denote the optimum value of R_s at $r_s = r_s^*$, and let R^* denote the average R_s^* over all SPs.

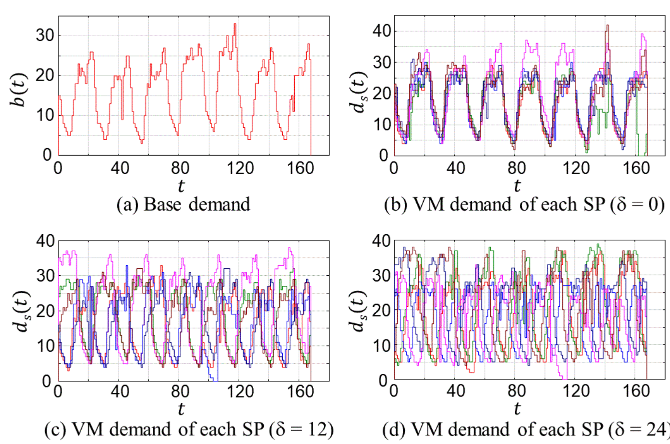


Fig. 3. (a) Example of base demand, (b)-(d) examples of SP demand when $S = 6$

B. Properties of ROD

First, we investigate the influence of p, the normalized unit price of ODI, on r_s^* in ROD. We define the RI ratio R_s as the ratio of VM demand satisfying $d \leq r_s$, i.e., $R_s \equiv \sum_{d=0}^{r_s} g_s(d)$. Let R_s^* denote the optimum value of R_s at $r_s = r_s^*$, and let

[4]We also observed the similar change pattern for all the 212 days.

R^* denote the average R_s^* over all SPs. Figure 4(a) plots R^* obtained by (2) against p when applying the base demand $b(t)$ of PowerInfo VoD from the x-th day, where $x = 1$, 20, 40, 60, 80, 100, 120, and 140, to $g_s(d)$. Moreover, in Fig. 4(b), we show the results when setting the truncated normal distribution with minimum of zero, maximum of 1.000, mean of 500, and standard deviation of σ_N, where $\sigma_N = 50$, 100, 150, 200, and 250, to $g_s(d)$, and we show the results when setting the Zipf distribution $d^{-\theta}/\sum_n n^{-\theta}$, where $\theta = 0.2$, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6, to $g_s(d)$ in Fig. 4(c).

We confirmed that the p-R^*curves were almost identical independently of $g_s(d)$. As p increased, ODI was comparatively expensive than RI, and the increase of cost for SPs caused by obtaining ODIs when the VM demand exceeds r_s was larger than that caused by unused RIs when the VM demand falls below r_s. Therefore, R^* increased as p increased. For example, R^* was about 0.4 and 0.6 when $p = 1.67$ and 2.5 which corresponds to the one-year term RI and three-years term RI in Amazon EC2, respectively. Moreover, we plot F, the average normalized fee paid by each SP in each TS, against p. When applying the truncated normal distribution to $g_s(d)$, F increased as σ_N increased because more RIs were unused as σ_N increased. When applying the Zipf distribution to $g_s(d)$, F increased as θ decreased because the variance of VM demand increased as θ increased.

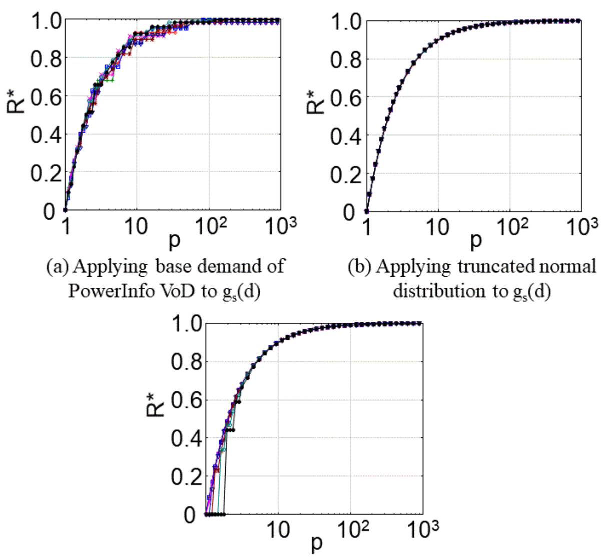


Fig. 4. Average optimum ratio of RI against normalized unit price of ODI in ROD

C. Properties of RISE

First, we set $R_s = R$ to all SPs of $\boldsymbol{S}$ and derive F_s by (12) for given R, p and α_s in RISE. Let F denote the average F_s over all SPs of $\boldsymbol{S}$, and Fig. 6 plots F against R. F_s in RISE is independent of the distribution and pattern of VM demand, and we used $d_s(t)$ of $\delta = 0$ as an example. There are two conflicting factors affecting F_s by increasing R_s: (i) the reduction effect of F_s due to decrease of expensive ODIs obtained and (ii) the increase effect of F_s due to increase of

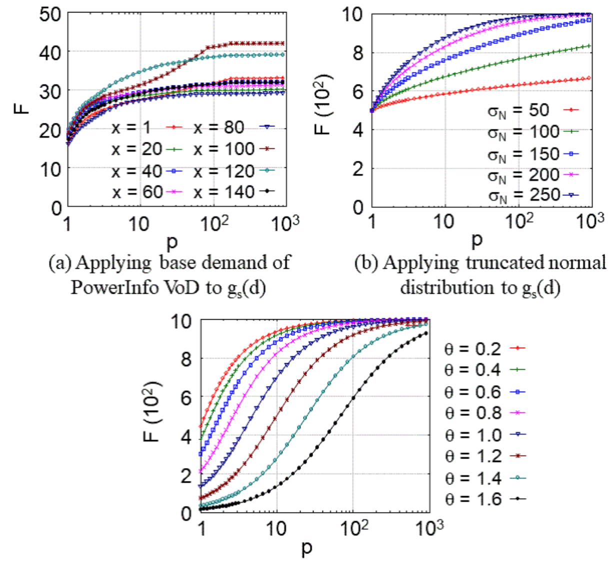


Fig. 5. Average normalized fee paid by each SP in each TS in ROD

unused RIs. In the small-R_s region, the effect of decreasing expensive ODIs obtained is dominant, so F_s decreased as R_s increased. On the other hand, in the large-R_s region, the effect of increasing unused RIs is dominant, so F_s increased as R_s increased. Therefore, there existed the optimum value of R_s, R_s^*, for SPs minimizing F_s in the range of $0 < R_s < 1$. As p increased, the influence of change in R_s on the number of ODIs obtained increased, so R_s^* increased. However, when α_s was large, the effect of smoothing the VM demand through the TR was large, so the sensitivity of R_s^* against p decreased, and R_s^* was about 0.45 independently of p.

Figures 7(a) and 7(b) plot R^* and F against α_s when deriving r_s^* by (10) from giving p and α_s. Because R_s^* was not obtained by a closed form, we selected R_s minimizing F_s as R_s^* when setting R_s to x percentile of $g_s(d)$, where x is integers in $1 \leq x \leq 100$. Like ROD, as p increased, ODI was more expensive than RI, so R^* increased. There are two conflicting factors affecting R_s^* by increasing α_s: (i) the increase effect of R_s^* due to increase of $C_s(T)$ through providing unused RIs to the TR and (ii) the decrease effect of R_s^* due to increase of VMs which can be utilized at peak hours with small R_s^*. When p was small, the former effect was dominant, and R_s^* increased as α_s increased in the small-α_s region; whereas the latter effect was dominant, and R_s^* decreased as α_s increased in the large-α_s region. On the other hand, when p was large, the latter effect was dominant in wide range of α_s, so R_s^* monotonically decreased as α_s increased. Moreover, F also monotonically decreased with increase of α_s, and the degree of decrease of F increased as p increased because the influence of $C_s(T)$ on F grew.

Let α^* denote the average of α_s^* over all SPs of $\boldsymbol{S}$ when optimally designing r_s and α_s by (10) and (11). Figure 8(a) plots α^* in RISE as well as R^* in RISE and ROD against p. Because α_s^* cannot be obtained by a closed form, we selected α_s minimizing R_s^* among the set of α_s at the interval of 0.01 in $0 \leq \alpha_s \leq 1$ as α_s^*. As shown in Fig. 7(a), when p was small, the value of α_s maximizing R_s^* decreased as p increased, so α^* sharply decreased as p increased. When p was larger than about seven, α^* was close to zero. Moreover, as p increased, R^* sharply increased in the small-p region, and R^* gradually increased in the large-p region. We also confirmed that RISE increased R^* compared with ROD when p was small. Figure 8(b) plots F in RISE and ROD against p, and we confirmed that F in RISE was smaller than that in ROD when p was small.

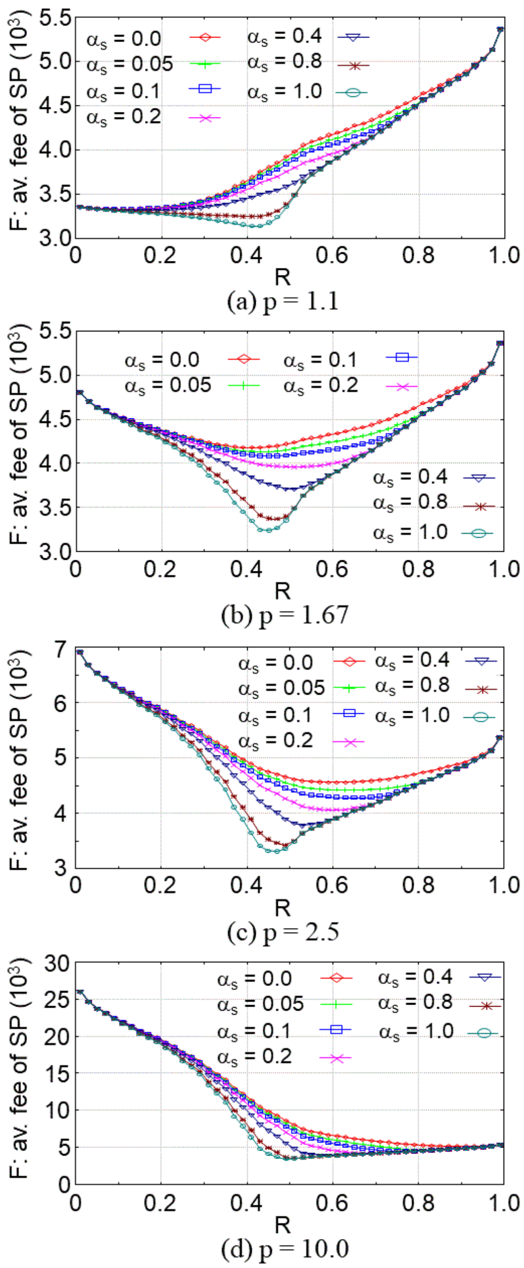


Fig. 6. F against R for given p and α_s in RISE

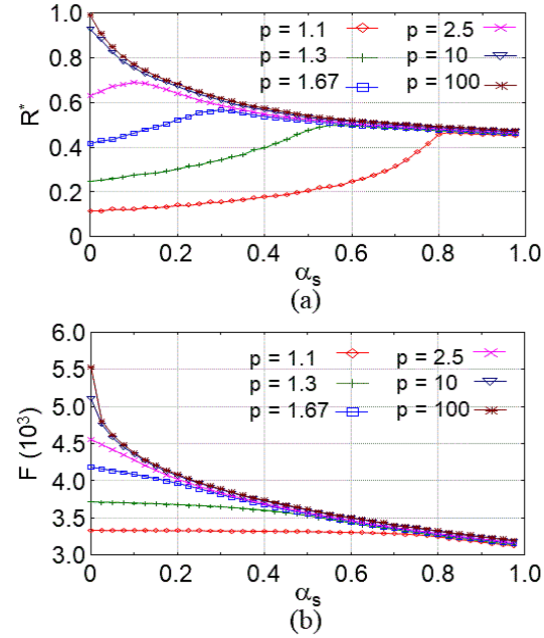


Fig. 7. (a) R^* against α_s in RISE, (b) F against α_s in RISE

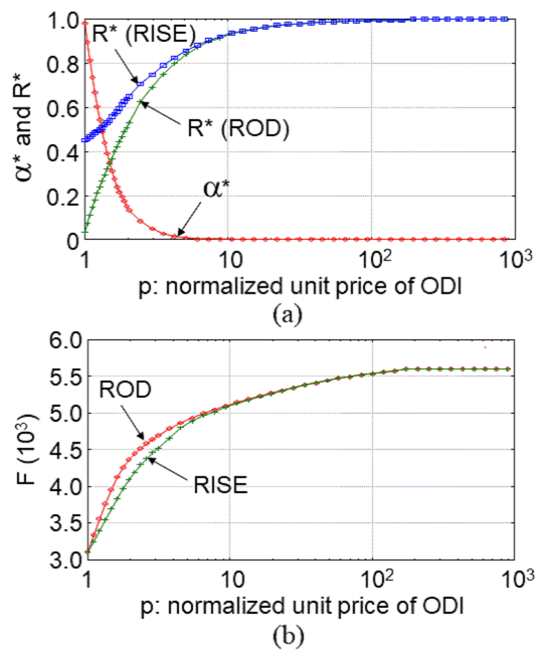


Fig. 8. (a) α^* and R^* against p in RISE, (b) F against p in RISE

D. Properties of RIMA

In RIMA, r_s^* depends on the time series of VM demand of other SPs, so SP s cannot derive R_s^* in advance. Hence, we set the identical value R to R_s of all SPs of $\boldsymbol{S}$, and we set the R percentile of $g_s(d)$ to r_s, where R was an integer of $1 \leq R \leq 100$. For five values of δ, Fig. 9 plots F against R when F was derived by (16) from given p and R. Like RISE, in the small-R region, the reduction effect of decreasing the number of ODIs obtained was dominant on F, so F decreased as R increased. On the other hand, when R was large, the effect of increasing the unused RIs was dominant on F, so F increased as R increased. As p increased, the influence of changing R on the number of ODIs obtained increased, so the optimum R minimizing F increased. Moreover, as δ increased, the chance trading VMs among SPs increased, so F decreased.

Figure 10 plots R^* and F against p in RIMA with five values of δ and ROD when setting R to R^* minimizing F, the average F_s of all SPs. As p increased, both R^* and F increased. When p was smaller than about two, the cost of occurring unused RIs was larger than the cost obtaining ODIs in RIMA. As δ increased, the possibility of occurring unused RIs decreased, so R^* increased with the increase of δ when p was smaller than about two. On the other hand, when p was larger than about two, the cost of obtaining ODIs was larger than the cost of occurring unused RIs, so reducing ODIs obtained by increasing R was desirable for SPs. To reduce the number of ODIs obtained, SPs needed to set a larger value to R as δ decreased, so R^* increased as δ decreased. Moreover, as δ increased, the effect of VM trading through the TR improved, and the number of ODIs obtained decreased, so F decreased.

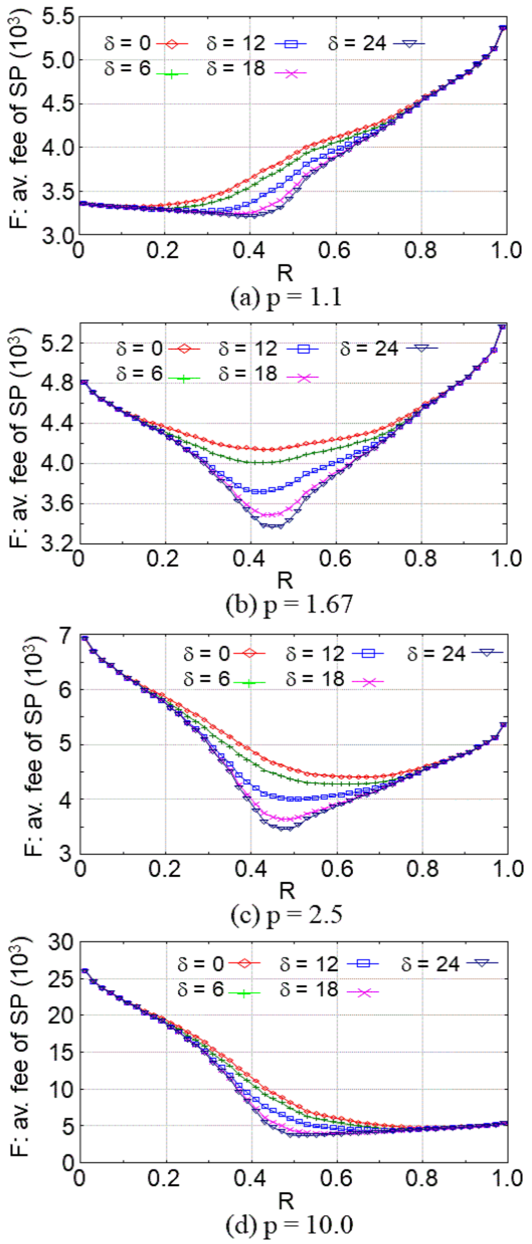


Fig. 9. F against R for given p in RIMA

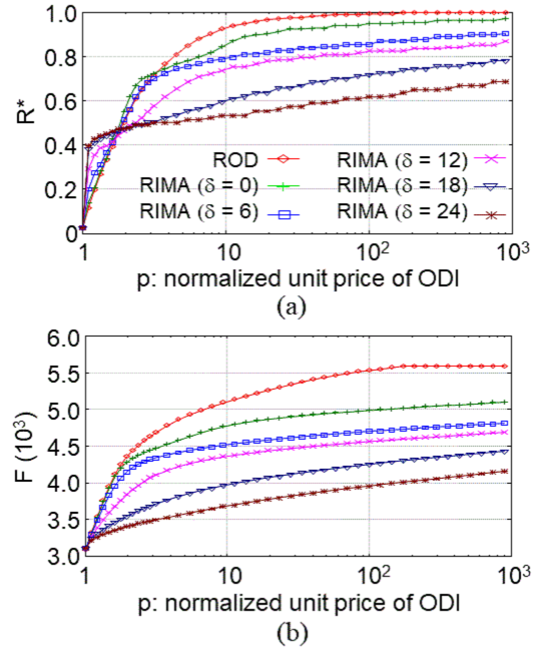


Fig. 10. (a) R^* against p in RIMA, (b) F against p in RIMA

E. Comparing Methods

As shown in Figs. 8 and 10, F_s decreased by using RISE or RIMA compared with ROD. As p, the normalized unit price of ODI, increased, R^* and F_s increased, so an InP can increase R^*, i.e., the RI ratio, while keeping the total fee of SPs constant by increasing p in RISE and RIMA. In this section, we clarify the effectiveness of RISE and RIMA by comparing the number of VMs required by an InP to prepare in RISE, RIMA, and ROD, when setting p of each method so that F_s was identical among these three methods. Let F_{ROD} denote the value of F in ROD when setting $p = P_{ROD}$. In the following evaluation, we set $P_{ROD} = 1.67$ and 2.5 which corresponds to the ratio of unit price of ODI against that of RI of one-year term and three-years term in Amazon EC2, respectively.

Let P_{RISE} and P_{RIMA} denote the value of p giving $F = F_{ROD}$ in RISE and RIMA, respectively, and Fig. 11 plots P_{RISE} and P_{RIMA} for five values of δ. As shown in Fig. 10(b), when δ was large, the increase of F was gradual with increasing p in RIMA, so F cannot reach F_{ROD} even if we set p to a huge value. Therefore, we set the upper limit of p to 1,000. In RISE, R_s^* depended on only $g_s(d)$ and p, so P_{RISE} was independent of δ. On the other hand, in RIMA, F decreased as δ increased as shown in Fig. 10(b), so P_{RIMA} increased with increase of δ. In the following evaluation, we set p in RISE and RIMA to P_{RISE} and P_{RIMA}, respectively.

1) Number of VMs Prepared by InP: Let Z_r and Z_o denote the number of VMs required by an InP to prepare for providing RIs and ODIs, respectively, and Fig. 12 plots Z_r of each method for five values of δ. Z_r was independent of δ in ROD

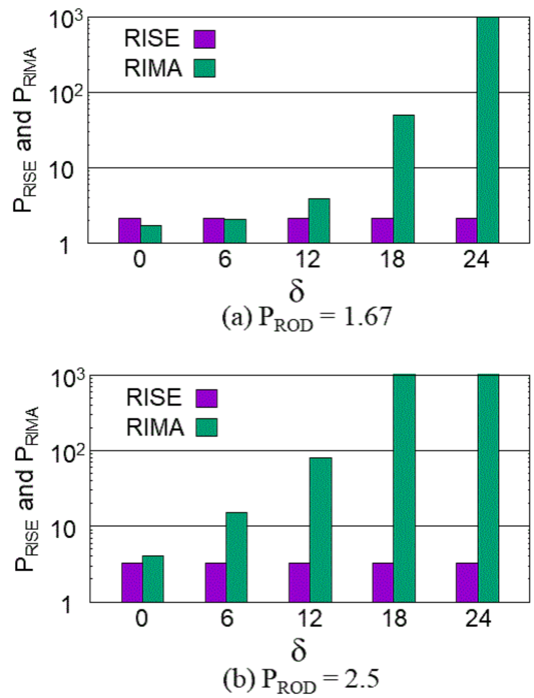


Fig. 11. Value of p satisfying $F = F_{ROD}$ in RISE and RIMA

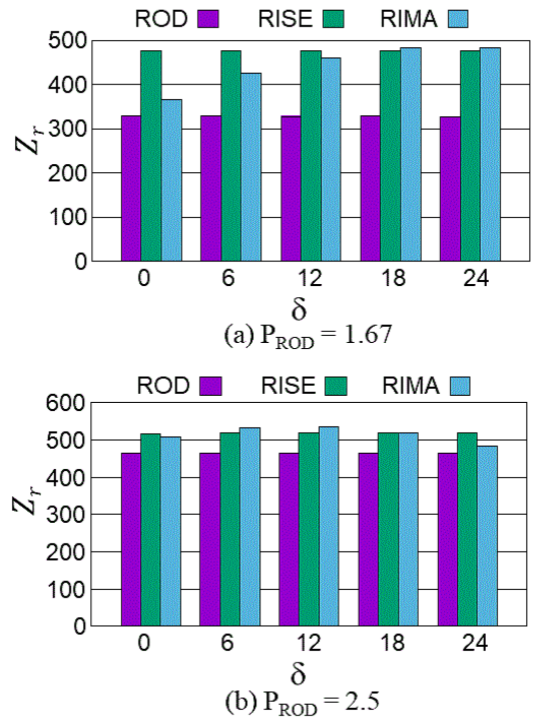


Fig. 12. Z_r, total number of VMs prepared by InP for RIs

and RISE, whereas Z_r increased as δ increased in RIMA[5]. We confirmed that RISE increased the number of RIs contracted by SPs independently of δ, compared with ROD.

As mentioned in Section III-C, an InP provides $V^o(t)$ VMs to SPs at TS t from Z_o VMs prepared for ODIs. For simplicity, we assume that $V^o(t)$ obeys a normal distribution, and we design Z_o by $Z_o = \mu_V + 3\sigma_V$ where μ_V and σ_V is the mean and standard deviation of $V^o(t)$, respectively, so that the probability that VMs prepared for ODI is in short supply is 0.3%[6]. Using $V^+(t)$ and $V^-(t)$ defined by (3) and (5), $V^o(t)$ is obtained by $V^o(t) = V^-(t)$ in ROD and $V^o(t) = \max\{V^-(t) - V^+(t), 0\}$ in RISE and RIMA. Figure 13 shows Z_o of the three methods against δ. As δ increased, the VM demand was smoothed among SPs, so both μ_V and σ_V decreased, and Z_o decreased in all the three methods. Compared with ROD, Z_o decreased by about 75% to 100% in RISE, and Z_o decreased by about 50% to 100% in RIMA. The reduction effect of Z_o increased as δ increased, and the reduction effect of Z_o in RISE was larger than that in RIMA when δ was small.

Figure 14 plots the total number of VMs required by an InP to prepare, i.e., $Z_r + Z_o$. Using RISE and RIMA, although Z_r increased as shown in Fig. 12, the total number of VMs which an InP is required to prepare decreased by several percent to about 20% because the reduction effect of Z_o was large as shown in Fig. 13.

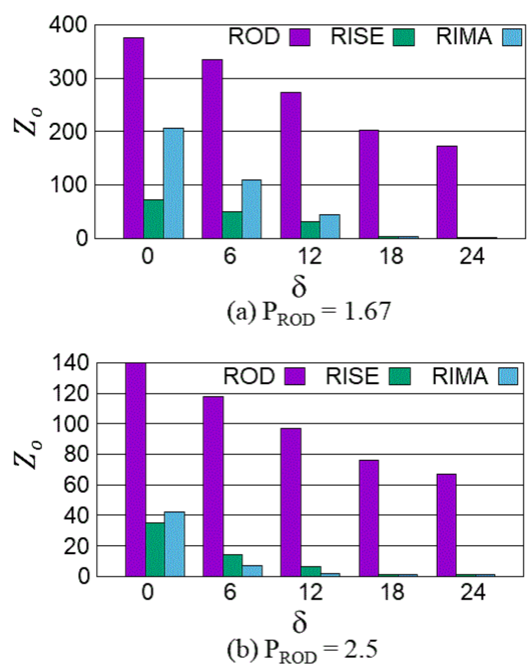


Fig. 13. Z_o, total number of VMs prepared by InP for ODIs

[5] As shown in Fig. 11, when $P_{ROD} = 2.5$ and $\delta = 18$ or 24, P_{RIMA} was set to the upper limit of 1,000, and $P_{RIMA} < P_{ROD}$, so Z_r was slightly smaller than that when $\delta = 12$ in RIMA.

[6] We will investigate the design method of Z_o when $V^o(t)$ obeys any distribution in future.

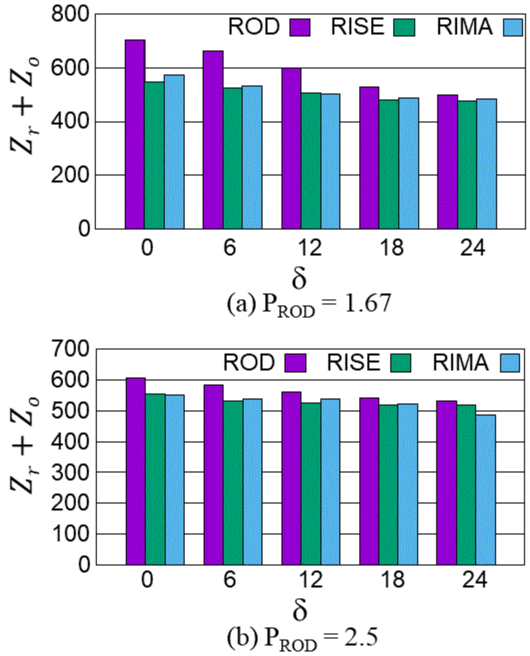


Fig. 14. Total number of VMs prepared by InP

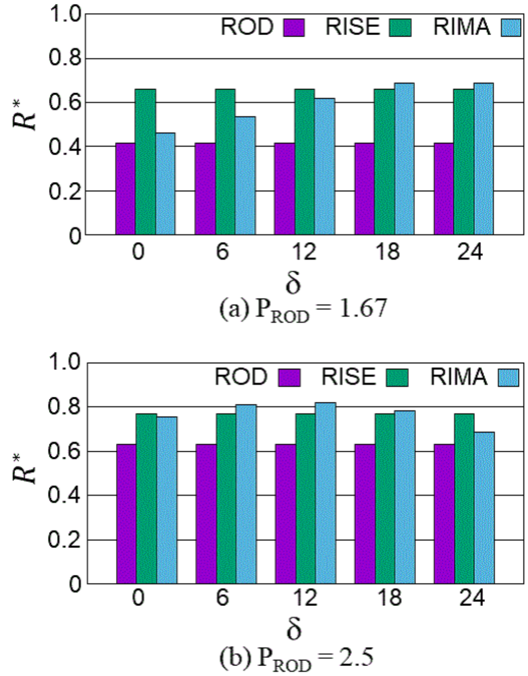


Fig. 15. Ratio of VMs prepared for RIs among all VMs prepared by InP

2) RI Ratio: Figure 15 plots R^*, the average RI ratio of each method, against δ, and we confirmed that both RISE and RIMA dramatically improved R^* compared with ROD. In RISE, R^* improved about 60% when $P_{ROD} = 1.67$ and about 25% when $P_{ROD} = 2.5$ independently of δ, compared with ROD. On the other hand, the effect of improving R^* in RIMA depended on δ, and R^* in RIMA improved about 10 to 70% compared with ROD. In RIMA, optimally designing r_s^* is difficult, and an InP needs to provide a mechanism to let SPs set R_s to the optimum value R_s^* because of the positive externality as mentioned in Section III-E3. On the other hand, in RISE, r_s depends on only $g_s(d)$ and p, so SP s can easily derive r_s^* as described in Section III-D3, and SPs are motivated to set r_s to r_s^*. In sum, we conclude that RISE is more desirable than RIMA as a method to improve the RI ratio by trading VMs among SPs through the TR.

V. Related Works

Several authors proposed optimal strategies of SPs to obtain VMs from InPs when multiple charging plans existed [2][12][22]. Genez et al. proposed an optimum scheduling method of obtaining RIs and ODIs so that the total cost was minimized under the SLA constraint for workflow presented by DAG (Directed Acyclic Graph) [12]. Ai et al. proposed algorithms which efficiently solved the optimum selection problem of cloud providers as well as charging plans so that the competitive ratio was minimized when future demand was unknown [2]. Moreover, by the two-stage Stackelberg game, Valerio et al. jointly solved the problems of setting the number of VMs obtained from IaaS providers, considering SLA of multiple SaaS providers of web services and setting the prices of IaaS provides in Amazon EC2 [22]. However, these methods aimed for deriving the optimum amount of resources which SPs obtained from InPs, and they did not consider improving the RI ratio.

Moreover, several authors have investigated cloud federation which tried to stabilize the revenue of cloud providers by trading the unused resources among multiple cloud providers [9][16][19]. Li et al. proposed methods to maximize the revenue of cloud providers by optimally designing all the trading price, job scheduling, and server provisioning using double auction, when trading VMs among multiple cloud providers [16]. Samman modeled the cloud federation by a repeated game in which each cloud provider behaved to maximize the long-term profit and investigated the realized state [19]. Darzanos et al. also analyzed the realized states in the cloud federation on the three cooperation types, i.e., strong, weak, and elastic, when distributing the profit to cloud service providers based on the Shapley value of cooperative game [9]. However, cloud federation assumes a trade of VMs among InPs, instead of trading VMs among SPs, and the cloud federation requires cooperation among multiple InPs.

VI. Conclusion

In this paper, we proposed VM trading methods among SPs to improve the RI ratio by applying unused RIs of SPs with VM demand less than r_s, the amount of contracted RIs, to SPs with VM demand greater than r_s through the trading room (TR). As the way of trading VMs among SPs, we investigated two approaches: RI with Self-help Effort (RISE) and RI with Mutual Aid (RIMA). In RISE, VMs were provided from the TR without fee for all the unsatisfied VM demand of SPs, and F_s, the fee of SP s, was determined by only $d_s(t)$, the VM demand of SP s in time slot (TS) t, and r_s. In RIMA, on the other hand, only VMs provided from SPs having unused

RIs were distributed to SPs with unsatisfied VM demand, and SPs still having unsatisfied VM demand needed to obtain VMs by ODI, so F_s depended on the pattern of VM demand and r_s of other SPs. Through numerical evaluation using the demand pattern of the commercial VoD service, we confirmed that the number of VMs required by an InP to prepare for ODI decreased by 50% to 100%, the total number of VMs required by an InP to prepare decreased by several to 20%, and the RI ratio increased by about 10% to 100% by using the proposed methods compared with the existing method without VM trading. Among the two proposed methods, RISE was more desirable because the improvement of RI ratio was more remarkable in RISE, and SPs were motivated to set r_s to the optimum value r_s^*. In future, we will investigate design methods of VM resources of an InP when the VM demand of SPs obeys any distribution. Moreover, we will also investigate VM trading methods when the future VM demand of SPs is unknown.

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