Proposal and Analysis of Biologically-inspired Symbiotic P2P File-sharing Networks

TOHRU MORIMOTO
Osaka University
Graduate School of
Information Science and Technology
1-5 Yamadaoka, Suita, Osaka
JAPAN
t-morimoto@ist.osaka-u.ac.jp

NAOKI WAKAMIYA
Osaka University
Graduate School of
Information Science and Technology
1-5 Yamadaoka, Suita, Osaka
JAPAN
wakamiya@ist.osaka-u.ac.jp

MASAYUKI MURATA
Osaka University
Graduate School of
Information Science and Technology
1-5 Yamadaoka, Suita, Osaka
JAPAN
murata@ist.osaka-u.ac.jp

Abstract: Recently, various overlay networks have been widely deployed over physical IP networks. Since selfish behavior of overlay networks to satisfy demands of their applications and users often conflicts with each other, performance of the overall network system and quality of service offered to users easily deteriorate. To tackle the problem, our research group proposes the framework called *overlay network symbiosis* based on the biological symbiosis model where different bacteria coexist in the shared medium. In the overlay network symbiosis, overlay networks directly and/or indirectly interact with each other through the shared environment and accomplish cooperative or collaborative control. In this paper, as an example of biologically-inspired symbiotic overlay networks, we propose a mechanism that enables different P2P file-sharing networks to cooperate and live together with mediation of a portal server. In our proposed mechanism, the portal server provides users with transparent utilization of multiple P2P file-sharing networks by handling search requests and shared files in place of users. Through numerical analysis, we showed that the proposed mechanism improved the hit ratio of search requests in comparison to the scenario where P2P file-sharing networks were independent.

Key–Words: Biological Symbiosis Model, P2P File-sharing, Cooperative Network, Numerical Analysis

1 Introduction

With emerging needs for application-oriented services, various overlay networks such as P2P (Peer-to-Peer) networks, Grid networks, and CDN (Content Delivery Network) have been widely deployed over physical IP networks. They are different in targeted application-oriented performance, network topology, and the amount and pattern of communication. Since each overlay network behaves in a selfish manner to satisfy demands of its applications and users, coexistence of multiple overlay networks often causes various problems [1, 2]. When overlay networks share and compete for the same physical network resources such as link and router, chain of selfish control leads to performance degradation and even the instability of a system. For example, we assume that an overlay network changes its topology to use less congested links to enhance throughput. Other overlay networks using those uncongested links experience performance degradation caused by increase of traffic. Since the affected networks are also selfish and greedy in improving the performance, they actively change their topology accordingly. Consequently, the influence extends to the whole network. As an another example, let us consider competition of P2P file-sharing networks for information resource. Each network attempts to attract more users and increase the number and kinds of shared files by a user-friendly interface, high hit ratio of search, fast file retrieval, and anonymity. Because of the diversity in usability, performance, and type of shared files, users may prefer one network to others and consequently the availability of files differs among networks. Therefore, users need to participate in two or more P2P file-sharing networks to get their desired files or share their files with many other users.

In order to improve the performance of the overall system, several cooperative mechanisms such as information exchange among overlay networks [3, 4, 5] and routing overlay [6] have been proposed. In [4], the authors investigated a spectrum of cooperation among coexisting overlay networks. They described kinds of cooperation such as sharing measurement information, sharing control information, cooperative query forwarding, and inter-overlay traffic engineering. As an example, they proposed an architecture called Synergy where overlay networks cooperated with each other in inter-overlay routing. The synergy network relays long-lived flows so that they traverse better paths than ones determined by the physical routing. It is shown that such inter-overlay routing improves performance in terms of latency, throughput, and loss.

Our research group considers the framework called *overlay network symbiosis* for cooperation among overlay networks that share and compete for network and information resources [7]. In the overlay network symbiosis, cooperation is based on the model of symbiotic living organisms in the ecosystem. In the ecosystem, symbiosis is often observed among living organisms of different species, groups, and individuals in the shared environment. Symbiosis emerges from direct and/or indirect interaction among organisms. In [8], the authors established the mathematical model of biological symbiosis where closely related bacterial strains lived together in a reactor by exchanging metabolites through their cell and the medium. Based on the biological symbiosis model, we can model and analyze symbiosis among overlay networks. We regard overlay networks as bacteria, direct interaction such as message exchanges and indirect interaction such as competition for shared resources as exchange of metabolites among cells, and the shared environment such as physical networks, inter-overlay network, and some mediation mechanism as a reactor. In this paper, to demonstrate an example of biologically-inspired symbiotic overlay networks, we propose a mechanism that enables different P2P file-sharing networks to cooperate and live together with mediation of a portal server.

The rest of the paper is organized as follow. In Section 2, we briefly introduce the mathematical model of co-existence of bacterial strains and explain the overlay network symbiosis. We propose a mechanism and a model of biologically-inspired symbiotic P2P file-sharing networks in Section 3. In Section 4, we show results of numerical analysis, where the effectiveness of symbiosis is evaluated by the hit ratio of search requests. Finally, we conclude this paper and describe future work in Section 5.

2 Overlay Network Symbiosis

In this section, we introduce the mathematical model of co-existence of bacterial strains and the overlay network symbiosis based on the biological model.

2.1 Biological Symbiosis Model

In [8], the authors proposed a mathematical model of a mechanism that permitted two types of bacterial strains to live together by exchanging metabolites through a reactor. Bacterial strains have a metabolic network of generating metabolite S_2 from other metabolite S_1. Metabolites diffuse in and out of a cell through membrane depending on the difference in metabolic concentrations (Fig. 1).

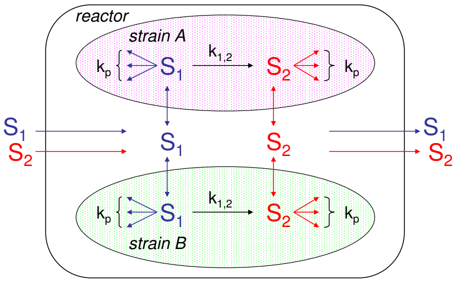

Figure 1: Symbiosis model of bacteria

Temporal dynamics of concentrations of metabolites in a cell of strain $i \in \{A, B\}$ are formulated as,

$$\frac{ds_1^{(i)}}{dt} = \frac{P}{V}(s_1^{(R)} - s_1^{(i)}) - (k_{1,2}^{(i)} + k_p)s_1^{(i)}, \qquad (1)$$

$$\frac{ds_2^{(i)}}{dt} = \frac{P}{V}(s_2^{(R)} - s_2^{(i)}) + k_{1,2}^{(i)}s_1^{(i)} - k_p s_2^{(i)}, \qquad (2)$$

where P stands for the permeation coefficient of cell membrane, V does for the average volume of a cell. $s_{\{1,2\}}^{(i)}$ and $s_{\{1,2\}}^{(R)}$ are metabolite concentrations in a cell of strain i and in the reactor, respectively. k_p is the metabolite consumption rate in a cell. $k_{1,2}^{(i)}$ is the metabolite conversion rate in a cell of strain i.

Next, metabolite concentrations in the reactor evolve as,

$$\frac{ds_1^{(R)}}{dt} = D(s_1^{(0)} - s_1^{(R)}) + \sum_{i \in \{A,B\}} X^{(i)} P(s_1^{(i)} - s_1^{(R)}), \qquad (3)$$

$$\frac{ds_2^{(R)}}{dt} = D(s_2^{(0)} - s_2^{(R)}) + \sum_{i \in \{A,B\}} X^{(i)} P(s_2^{(i)} - s_2^{(R)}), \qquad (4)$$

where $X^{(i)}$ stands for the number of cells of strain i per volume in the reactor. The fresh medium containing metabolites of concentration $s_{\{1,2\}}^{(0)}$ is added to the reactor at the constant rate and the culture is drained at the same rate. D means the resultant dilution rate.

Change in population of cells is formulated as,

$$\frac{dX^{(i)}}{dt} = \mu^{(i)} X^{(i)} - DX^{(i)}, \qquad (5)$$

where the growth rate $\mu^{(i)}$ is defined as,

$$\mu^{(i)} = \alpha s_1^{(i)} s_2^{(i)}. \qquad (6)$$

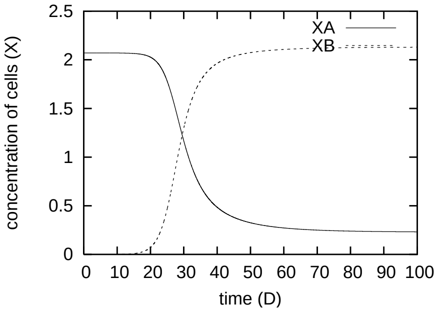

Figure 2: Population of bacterial strains

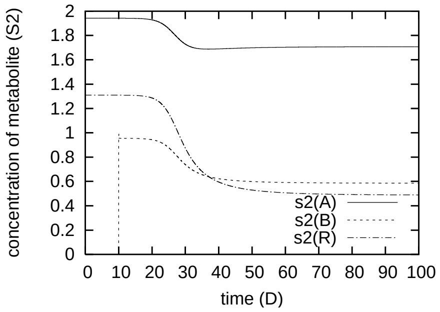

Figure 3: Concentration of metabolite S_2

Eq. (6) implies that a cell with high metabolite concentration grows fast. Here, $\alpha > 0$ is a constant.

Figures 2 and 3 show results of numerical analysis where $s_1^{(0)} = 10.0$, $s_2^{(0)} = 0.0$, $\frac{\alpha}{D} = 1.0$, $\frac{P}{D} = 1.0$, $\frac{k_p V}{P} = 1.0$, $\frac{k_{1,2}^{(A)} V}{P} = 5.0$, and $\frac{k_{1,2}^{(B)} V}{P} = 0.4$. In the figures, X axis corresponds to time and Y axis shows the population of cells and the concentration of metabolite S_2, respectively. At first there is only bacterial strain A in the reactor. At time $10D$, bacterial strain B, which differs from bacterial strain A only in the conversion rate, i.e. $k_{1,2}^{(B)} < k_{1,2}^{(A)}$, is introduced into the reactor. As shown in Fig. 2, the population of bacterial strain A that consumes metabolite S_1 faster than bacterial strain B decreases, after bacterial strain B with the lower conversion rate is added to the reactor. However, after a while, the concentrations of bacterial strains in the reactor become constant at time $90D$ and both are larger than zero. That is, they live together. In Fig. 3, it can be seen that $s_2^{(R)} < s_2^{(B)} < s_2^{(A)}$ holds in the stable condition. It implies that metabolite S_2 permeates cell membrane of both bacterial strains A and B to the reactor. Depending on parameter setting, symbiotic conditions where both bacterial strains take metabolites from the reactor, i.e. $s_2^{(B)} < s_2^{(R)}$ and $s_2^{(A)} < s_2^{(R)}$, or one bacterial strain supplies metabolites to another bacterial strain, e.g. $s_2^{(B)} < s_2^{(R)} < s_2^{(A)}$, also appear.

2.2 Biologically-inspired Overlay Network Symbiosis

Our research group proposes the framework called *overlay network symbiosis* based on the biological symbiosis model [7]. In [9], we regarded a reactor as a system, bacterial strains as overlay networks that offer a service to users, metabolite S_1 as a group of users, metabolite S_2 as the shared resource, the metabolite conversion rate in a cell as the number of users served per unit time, i.e. the service rate or service capacity of network, and X as the size of a network. Based on the mathematical model, we investigated conditions that made competing networks coexist. We showed that among networks more users received the service from a less loaded network, i.e. network with the lower metabolic concentration $s_1^{(i)}$. We also observed that network i with high metabolic concentration $s_2^{(i)}$ released the occupied resource for the use of other networks. More importantly, we revealed that there were conditions where a single overlay network could not survive alone but could live together by harmonious coexistence of other networks.

3 Biologically-inspired Symbiotic P2P File-sharing Networks

In this section, as an example of symbiosis of overlay networks based on our overlay network symbiosis, we propose a mechanism of symbiotic P2P file-sharing networks with a portal server and its mathematical model for analysis.

3.1 Symbiotic P2P File-sharing Networks with Portal Server

We assume that there are various P2P file-sharing networks. So that P2P file-sharing networks can cooperate with each other in sharing files by exchanging search requests and shared files, we introduce a portal server as the shared environment. A portal server belongs to multiple P2P file-sharing networks as a peer in order to send and withdraw search requests and to upload and download shared files in place of users. Users can search, get, and share files through a portal server without being aware of existence of P2P file-sharing networks (Fig. 4).

When a user registers information resources such as a search request and a file to share to a portal server, the portal server first deposits them in its buffers. Depending on condition of P2P file-sharing networks, it issues or withdraws a request in a request queue and

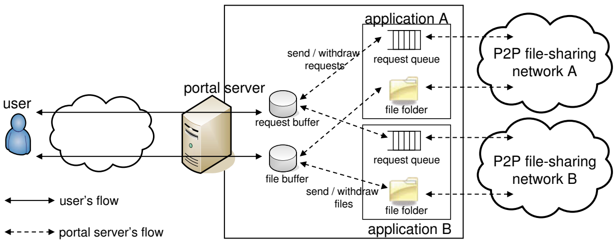

Figure 4: Symbiotic P2P file-sharing networks with a portal server

puts or withdraws a file in a shared file folder. For example, when the number of files shared in a P2P file-sharing network is small, a portal server supplies files from its file buffer to the network in order to foster sharing and exchanging files in the network. On the contrary, a portal server withdraws files from a loaded P2P file-sharing network and supplies them to other networks. When a request is served by a P2P file-sharing network and a portal server obtains a corresponding file from a peer participating in the network, it is deposited in the shared file folder or the file buffer while sending it to the requesting user.

3.2 Biologically-inspired Model of Symbiotic P2P File-sharing Networks

We can model the above proposed mechanism based on the biological symbiosis model by regarding a portal server as a reactor, P2P file-sharing networks as bacterial strains, requests as metabolite S_1, and files as metabolite S_2. A portal server adjusts the number of requests to be served by, and the number of files to be shared on P2P file-sharing networks depending on the condition of each network. When we regard requests and files as metabolites, this corresponds to exchange of metabolites between bacterial strains through the medium in a reactor.

However we cannot directly apply the biological symbiosis model explained in Section 2.1 to model the symbiotic P2P file-sharing networks. In P2P file-sharing networks, there exist users participating to P2P file-sharing networks without mediation of a portal server. We call them direct users hereafter. Direct users are peers constituting P2P file-sharing networks. In contrast, users of a portal server are called portal users. Direct users send requests and upload files directly to a P2P file-sharing network and obtain files directly from a P2P file-sharing network. Such user's direct interaction with P2P file-sharing networks corresponds to direct injection and extraction of metabolites to and from bacterial strains. However, neither of dynamics of metabolic concentrations in a cell, i.e. Eqs. (1) and (2) has such a term.

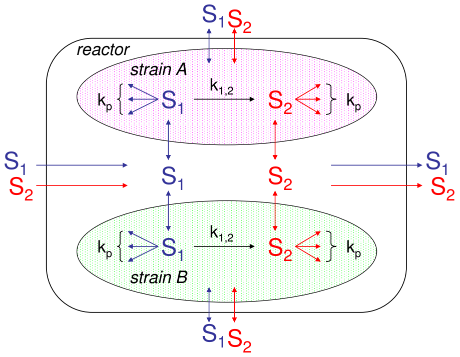

Figure 5: Extended bacterial symbiosis model

We extend the bacterial symbiosis model illustrated in Fig. 1 to a new model in Fig. 5. The difference is existence of arrows connecting inside of strains to outside of the reactor. When we define the metabolite concentrations added to the whole system as $s_{\{1,2\}}^{(U)}$ and the volume of reactor as V_R, $s_{\{1,2\}}^{(U)} V_R$ corresponds to the number of metabolites S_1 and S_2 in the fresh medium. Among them, $s_{\{1,2\}}^{(0)} V_R$ is added to the culture in the reactor and the remaining $V_R(s_{\{1,2\}}^{(U)} - s_{\{1,2\}}^{(0)})$ is directly added to bacterial cells. Here, $s_{\{1,2\}}^{(U)} - s_{\{1,2\}}^{(0)}$ means the metabolite concentration added to bacterial cells. Furthermore we assume that the fresh medium is evenly added to both strains. Then, temporal dynamics of metabolite concentrations in a cell are re-formulated as,

$$\begin{aligned}\frac{ds_1^{(i)}}{dt} &= \frac{P}{V}(s_1^{(R)} - s_1^{(i)}) - (k_{1,2}^{(i)} + k_p)s_1^{(i)} \\ &\quad + M_t\{\frac{1}{2}(s_1^{(U)} - s_1^{(0)}) - s_1^{(i)}\},\end{aligned} \tag{7}$$

$$\begin{aligned}\frac{ds_2^{(i)}}{dt} &= \frac{P}{V}(s_2^{(R)} - s_2^{(i)}) + k_{1,2}^{(i)} s_1^{(i)} - k_p s_2^{(i)} \\ &\quad + M_t\{\frac{1}{2}(s_2^{(U)} - s_2^{(0)}) - s_2^{(i)}\},\end{aligned} \tag{8}$$

where M_t stands for addition and drain rate of metabolites to and from bacterial strains per unit time. Temporal dynamics of metabolite concentrations in the reactor follow Eqs. (3) and (4). Change in population of cells follows Eq. (5).

We summarize parameter definition in Table 1. In the table, assuming that volume of cell is identical and one, we regard concentration as number. Based on the definitions, we derive temporal dynamics of symbiotic P2P file-sharing networks as following.

Table 1: Parameter definition

parameter	definition
$s_1^{(i)}$	the number of requests being served per peer in P2P file-sharing network i
$s_2^{(i)}$	the number of shared files per peer in P2P file-sharing network i
$s_1^{(R)}$	the number of requests that a portal server holds in buffer
$s_2^{(R)}$	the number of files that a portal server holds in buffer
$s_1^{(0)}$	the number of new requests that portal users register to a portal server per unit time
$s_2^{(0)}$	the number of new files that portal users register to a portal server per unit time
$s_1^{(U)}$	the total number of new requests that portal users and direct users issues per unit time
$s_2^{(U)}$	the total number of new files that portal users and direct users provide per unit time
$k_{1,2}^{(i)}$	rate of search completion in P2P file-sharing network i per unit time
k'_p	rate of disappearance of information resources from P2P file-sharing networks per unit time
P	rate of exchange of information resources between a P2P file-sharing network and a portal server per unit time
D	rate of registration and cancellation of information resources to and from a portal server by portal users per unit time
M_t	rate of uploading and downloading of information resources to and from P2P file-sharing networks by direct users per unit time
$\mu^{(i)}$	growth rate of P2P file-sharing network i
$X^{(i)}$	the number of participating peers in P2P file-sharing network i
α	growth coefficient ($\alpha > 0$)

First, temporal change in the number $s_1^{(i)}$ of requests being served per peer in P2P file-sharing network i is given by the following differential equation.

$$\frac{ds_1^{(i)}}{dt} = P(s_1^{(R)} - s_1^{(i)}) - k_{1,2}^{(i)} s_1^{(i)} - k'_p s_1^{(i)} + \frac{1}{2} M_t (s_1^{(U)} - s_1^{(0)}). \qquad (9)$$

where we denote $k_p + M_t$ as k'_p. $s_1^{(i)}$ is a quotient of the total number of requests divided by the number of participating peers in P2P file-sharing network i. $s_1^{(i)}$ changes in relation to the number $s_1^{(R)}$ of requests that a portal server holds (the first term in the right-hand side). The condition that $s_1^{(i)}$ is more than $s_1^{(R)}$ implies that more peers are searching or downloading files. Then, to reduce the load, the portal server withdraws requests from the P2P file-sharing network. $s_1^{(i)}$ decreases when corresponding downloading finishes (second term) and decreases for cancellation (third term). $s_1^{(i)}$ increases when direct users send requests (fourth term).

Next, temporal change in the number $s_2^{(i)}$ of files shared per peer in P2P file-sharing network i can be given by the following differential equation.

$$\frac{ds_2^{(i)}}{dt} = P(s_2^{(R)} - s_2^{(i)}) + k_{1,2}^{(i)} s_1^{(i)} - k'_p s_2^{(i)} + \frac{1}{2} M_t (s_2^{(U)} - s_2^{(0)}). \qquad (10)$$

$s_2^{(i)}$ is a quotient of the total number of shared files divided by the number of participating peers in P2P file-sharing network i. $s_2^{(i)}$ changes in relation to $s_2^{(R)}$ (first term). The condition that $s_2^{(i)}$ is more than $s_2^{(R)}$ implies that the P2P file-sharing network has a sufficient number of files. Then, a portal server stops offering files to the network to prevent excessive supply. $s_2^{(i)}$ increases when a portal server and direct users finish downloading files (second term) and decreases when a portal server and direct users stop sharing files (third term). $s_2^{(i)}$ increases when direct users upload files to share (fourth term).

Temporal change in the number $s_1^{(R)}$ of requests that a portal server holds in its buffer follows Eq. (3). $s_1^{(R)}$ increases when portal users register requests and decreases for cancellation (first term). To search files efficiently, a portal server sends requests to a P2P file-sharing network with the small number of requests being served or a P2P file-sharing network with the large number of participating peers (second term). On the other hand, a portal server withdraws requests from a P2P file-sharing network with the large number of requests being served.

Temporal change in the number $s_2^{(R)}$ of files that a portal server holds in its buffer follows Eq. (4). $s_2^{(R)}$ increases when portal users register files and decreases for cancellation (first term). A portal server uploads or withdraws files in relation to $s_2^{(i)}$ and $X^{(i)}$, i.e. the number of participating peers (second term).

Temporal change in the number $X^{(i)}$ of participating peers in P2P file-sharing network i follows Eq. (5). $X^{(i)}$ increases when a new user participates in and decreases for leave of peers. The growth rate $\mu^{(i)}$ is defined as a product of the number $s_1^{(i)}$ of requests and the number $s_2^{(i)}$ of shared files in P2P file-sharing

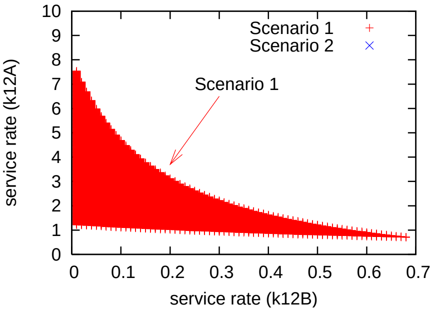

Figure 6: Scenarios leading to higher hit ratio

network i as Eq. (6) where $\alpha > 0$ is a constant.

4 Numerical Analysis

In this section, we evaluate biologically-inspired symbiotic P2P file-sharing networks through numerical analysis based on the biological mathematical model. Although we conducted through analysis against wide range of parameter setting, we show only few results due to space limitation.

4.1 Analysis Setting

We set P, k_p, and α at 1.0, and D and M_t at 0.01. The total number $s_1^{(U)}$ of new requests per unit time is set at 10.0 and the total number $s_2^{(U)}$ of new files per unit time is set at 2.0. Among new requests and files, those registered at the portal server are $s_1^{(0)} = 5.0$ and $s_2^{(0)} = 1.0$. We assume that there are two P2P file-sharing networks A and B whose service rate are $k_{1,2}^{(A)} > k_{1,2}^{(B)}$. We change the service rate $k_{1,2}^{(A)}$ from 0.1 to 10.0 and the service rate $k_{1,2}^{(B)}$ from 0.01 to 0.7 to evaluate its influence. We consider that a P2P file-sharing network is alive when the number of participating peers is larger than threshold H, which is empirically set at 0.00002. We should note here that absolute values of parameters are not related to realistic values. However we can analyze system behavior from their relative relationship.

We use the hit ratio as a performance measure. The hit ratio is the ratio of requests that can find a desired file in P2P file-sharing networks to the total number of requests. It is formulated as,

$$Hit\ ratio = \frac{\sum_{i\in\{A,B\}} X^{(i)} s_1^{(i)} k_{1,2}^{(i)}}{D s_1^{(0)} + M_t (s_1^{(U)} - s_1^{(0)})}. \tag{11}$$

In numerical analysis, we consider two scenarios. Scenario 1 is the case where there are both of direct and portal users. Scenario 2 is the case where the portal server doesn't exist and there are only direct users. In scenario 2, we set parameters as $P = 0.0$, $s_1^{(0)} = 0.0$, $s_2^{(0)} = 0.0$, $s_1^{(R)} = 0.0$, and $s_2^{(R)} = 0.0$.

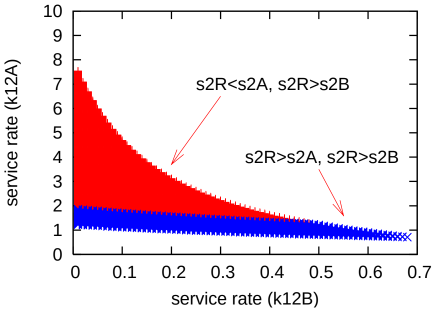

Figure 7: Status of the number of shared files

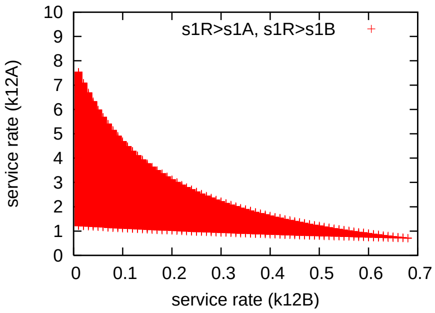

Figure 8: Status of the number of requests

4.2 Numerical Results

In Fig. 6, each point indicates a scenario which leads to the higher hit ratio under combinations of service rate $k_{1,2}^{(A)}$ and $k_{1,2}^{(B)}$. The region with points indicates conditions where P2P file-sharing networks live together. As shown in Fig. 6, the hit ratio of scenario 1 is always higher than that of scenario 2 at all points. It means that users can find more files in P2P file-sharing networks which are cooperatively utilized by the portal server. To analyze behavior of the portal server, we compare the number of requests and files that the portal server holds to that shared in P2P file-sharing networks in Figs. 7 and 8. As shown in the figures, when the service rate $k_{1,2}^{(A)}$ is small, $s_1^{(R)} > s_1^{(A)}$, $s_1^{(R)} > s_1^{(B)}$, $s_2^{(R)} > s_2^{(A)}$, and $s_2^{(R)} > s_2^{(B)}$ hold. That is, the portal server sends requests to both of P2P file-sharing networks and uploads files to the both as well. On the other hand, when the service rate $k_{1,2}^{(A)}$ is large, condition changes to $s_1^{(R)} > s_1^{(A)}$, $s_1^{(R)} > s_1^{(B)}$,

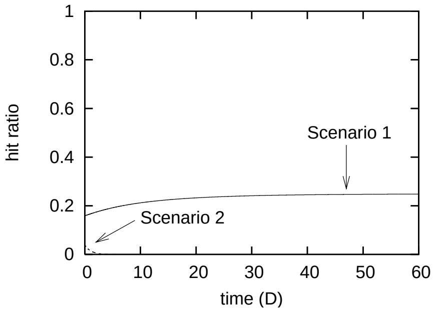

Figure 9: Transition of hit ratio

$s_2^{(R)} < s_2^{(A)}$, and $s_2^{(R)} > s_2^{(B)}$. In this case, although the portal server sends requests to both of P2P file-sharing networks, the portal server fosters effective file sharing by providing a P2P file-sharing network with the small service rate with not only files registered by portal users but also files obtained from other P2P file-sharing network with the higher service rate.

Next, Fig. 9 shows transition of the hit ratio where $k_{1,2}^{(A)} = 2.0$ and $k_{1,2}^{(B)} = 0.4$. As shown in Fig. 9, the hit ratio decreases and becomes zero, when two networks are independent in scenario 2. The reason can be explained as follows. Since the total number $s_1^{(U)}$ of new requests to P2P file-sharing networks is small, the number $s_1^{(i)}$ of requests and the number of $s_2^{(i)}$ shared files do not increase enough. It implies that networks are not effectively used or activated enough to grow. Users leave from P2P file-sharing networks and the networks eventually die. On the other hand, the hit ratio increases and becomes constant at time $50D$ when a portal server is introduced in scenario 1. This is because the portal server efficiently utilizes the small number of requests and files by using P2P file-sharing networks cooperatively.

5 Conclusion

In this paper, we proposed a mechanism that enabled different P2P file-sharing networks to cooperate and live together with mediation of a portal server. Through numerical analysis, it was shown that the hit ratio of P2P file-sharing networks was improved and P2P file-sharing networks can keep offering a service with the insufficient number of shared files.

As future research work, we will perform realistic simulation experiments taking into account network topology and other physical influence to investigate detailed behavior of P2P file-sharing networks mediated by a portal server.

Acknowledgements: This work was supported in part by the National Institute of Information and Communications Technology, Japan and “Global COE (Centers of Excellence) Program” of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References:

[1] M. Seshadri and R. H. Katz, “Dynamics of simultaneous overlay network routing,” Technical Report UCB//CSD-03-1291, Electrical Engineering and Computer Science (EECS), University of California Berkeley (UCB), Nov. 2003.

[2] L. Qiu, Y. R. Yang, Y. Zhang, and S. Shenker, “On selfish routing in Internet-like environments,” in *Proceedings of ACM SIGCOMM Conference 2003*, pp. 151–162, Aug. 2003.

[3] M. Kwon and S. Fahmy, “Toward cooperative inter-overlay networking,” in *Proceedings of the 11th IEEE International Conference on Network Protocols (ICNP)*, poster paper, Nov. 2003.

[4] M. Kwon and S. Fahmy, “Synergy: An overlay internetworking architecture and its implementation,” Technical Report, Purdue University, Oct. 2005.

[5] I. Stoica, D. Adkins, S. Zhuang, S. Shenker, and S. Surana, “Internet indirection infrastructure,” in *Proceedings of ACM SIGCOMM Conference 2002*, vol. 32, pp. 73–88, Aug. 2002.

[6] D. Andersen, H. Balakrishnan, F. Kaashoek, and R. Morris, “Resilient overlay networks,” in *Proceedings of 18th ACM Symposium on Operating Systems Principles*, vol. 35, pp. 131–145, Oct. 2001.

[7] N. Wakamiya and M. Murata, “Toward overlay network symbiosis,” in *Proceedings of the 5th International Conference on Peer-to-Peer Computing (P2P2005)*, pp. 154–155, Aug. 2005.

[8] T. Yomo, W.-Z. Xu, and I. Urabe, “Mathematical model allowing the coexistence of closely related competitors at the initial stage of evolution,” *Researches on Population Ecology*, vol. 38, pp. 239–247, Dec. 1996.

[9] N. Wakamiya and M. Murata, “Bio-inspired analysis of symbiotic networks,” in *Proceedings of 20th International Teletraffic Congress (ITC-20)*, June 2007.