Overlay Network Symbiosis: Evolution and Cooperation

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***Abstract*— Simultaneous overlay networks compete for physical network resources and disrupt each other. If they could establish cooperative relationships, the collective performance can be improved and they can coexist peacefully and comfortably. Taking inspiration from biology, in this paper we present a model of symbiotic overlay networks. Coexisting overlay networks dynamically evolve, interact with each other, and change their internal structures. Overlay networks in a symbiotic condition, i.e., mutualism, eventually establish the strong relationship and finally fuse into one. We first analyze characteristics of an overlay network which evolves based on three different models, i.e., the preferential attachment, random, and combination of them, by using mathematical analysis and simulation experiments. Next, we evaluate the effect of interconnecting two overlay networks from the viewpoint of the cost and the benefit.**

I. Introduction

With emerging needs for application-oriented network services, overlay networks have been widely deployed over physical IP networks. Since overlay networks share and compete for limited physical network resources, their selfish and independent behavior to pursue their own benefit and to maximize their own utility disrupts each other [1], [2], [3].

In [4], they investigated a spectrum of cooperation among coexisting overlay networks to enhance their collective performance and efficiently utilize network resources. They proposed an architecture where overlay networks cooperated with each other in inter-overlay routing. In this architecture, a message emitted by a node in one overlay network is forwarded to another which provides a shorter path to the destination. They also briefly described perspectives on other kinds of cooperation, such as sharing measurement information, sharing control information, cooperative query forwarding, inter-overlay traffic engineering, and merging overlays. In [5], they considered a hierarchical overlay model, in which overlay networks were interconnected by an upper level network of representative peers, called super peers. Although they claimed benefits of cooperation, we consider some questions must be answered to accomplish effective cooperation of overlay networks; how should each overlay network grow, how should overlay networks cooperate with each other, and how should each overlay network react to the cooperation?

The analysis on coexistence of competitors in the environment has been investigated in the field of biology [6], [7]. In the ecosystem, organisms in the same environment live together peacefully and comfortably through direct and/or indirect interactions with each other. In [6], they established a mathematical model of metabolic pathways of bacterial strains to elucidate mechanisms of coexistence of living organisms of closely related species (see Fig. 1). They revealed that the coexistence emerged not only from interactions among competitors, but also from changes of their internal states.

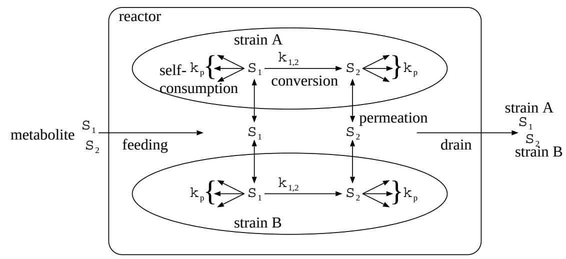


Fig. 1. Metabolic system of coexsiting bacteria

In [8], taking inspirations from biology, we proposed a model of overlay network symbiosis where the symbiosis among competing overlay networks was built on the shared physical network. In the model, we regard an overlay network as an organism, which evolves and expands as a new node joins, diminishes as a node leaves or halts, interacts with other overlay networks through direct and/or indirect communications, and changes its topology as a consequence of interactions. In this paper, to answer the first two questions among three stated above to some extent, we show results of our extensive analysis and evaluation of behaviors of overlay networks in the model of overlay network symbiosis.

The rest of the paper is organized as follow. In Section II, we describe the model of overlay network symbiosis. Then, in Section III, we analyze evolution of overlay networks on three different growth models. Section IV provides simulation results to see the effect of different types of cooperation. Finally, we summarize this paper and explain future directions in Section V.

II. Overlay Network Symbiosis

The coexistence of strains emerges from interactions through changes in the external states and resultant changes in the internal states. In the model of overlay network symbiosis, overlay networks evolve, interact with each other, and change their internal topologies. Cooperation of overlay networks emerges from independent and autonomous behaviors of nodes. By observing its own condition and surroundings, each node in an overlay network dynamically establishes and disconnects logical links to other nodes in the same overlay network. In addition, a node occasionally establishes a logical link to another overlay network. Through inter-overlay links, messages such as queries, responses, and files are interchanged among overlay networks. If both ends of an inter-overlay link consider it is worth interconnecting, the link is kept. Otherwise, it is disconnected. As time passes, those overlay networks that benefit from each other become tightly connected and they eventually fuse into one.

Assume that there are M heterogeneous overlay networks in a system. Each overlay network $w \in [1, M]$ starts with a small number of nodes $n_w(0) \geq 0$. In the rest of the paper, 'network' and 'overlay network' are used interchangeably.

A. Evolution

At each time step, new nodes join one or more networks. The number of nodes in overlay network w at time t is expressed as $n_w(t)(n_w(0) \geq 0)$. First, in joining an overlay network, a new node establishes one or more logical links to nodes that already present in the network.

There are variety of strategies in choosing nodes to connect to [9], [10], [11], [12]. For example, in [9], they considered so-called preferential attachment, where a node with more neighbors became a neighbor of a newly joined node more often than nodes with less neighbors. The preferential attachment leads to the power-law structure of a network, where the connectivity distribution follows the form $P(k) \sim k^{-\gamma}$.

B. Interconnection

Each node decides whether it establishes an inter-overlay link or not independently of the others. A node interconnecting overlay networks becomes a gateway node through which messages are exchanged among the cooperating networks. On the contrary to [5], where a designated representative node, called a super peer, always plays the role of a gateway node, any node can become a gateway node on its own decision in our model. The decision is made by a node independently of the others, but there must be coordination among gateway nodes in an overlay network to have efficient cooperation. Other networks can be found by using, for example, i3 [13]. To establish an inter-overlay link, a node emits a request message to a node of another network. On receiving the request, the node in the other network decides whether or not to accept the request taking into account the benefit and the cost.

The probability $p_{w,j}$ that node j in overlay network w newly establishes an inter-overlay link can be uniform among nodes, i.e., random interconnection. Based on the biological model, $p_{w,j}$ can be defined as a function of demand for files or the number of files that a peer has. If it is a monotonically increasing function of the number of files, a peer with more files has a higher probability to extend its hand to help others. On the contrary, if it is a monotonically decreasing function, a poor peer is eager to cooperate with other P2P networks to find more files and improve the perceived application-level QoS. When we define $p_{w,j}$ as a monotonically increasing function of the number of neighbors, i.e., degree $k_{w,j}$ of node j, we can expect efficient message dissemination [14]. In addition, the average distance between two arbitrary nodes in different networks is kept small as in a small world network.

C. Interaction

After establishing an inter-overlay link, a gateway node begins to relay messages among cooperating networks under a certain policy. In the case of P2P file-sharing networks, exchanging query and response messages improves the application-level QoS such as the probability of successful search at the sacrifice of the increased load on the system [15].

A gateway node in P2P network A forwards query messages to P2P network B. The gateway node aggregates response messages into one and then sends the merged message to the querying node over network A. If a gateway node deposits meta-information in response messages into its local cache, it does not need to forward query messages for the same or similar files any more. Taking into account the facts that message relaying puts some burdens on a gateway node, the available bandwidth is limited and asymmetric among upward and downward links, and the processing and buffering capabilities are also limited, the rate of message forwarding must be controlled. Furthermore, when P2P networks are heterogeneous, i.e., operated using different protocols, a gateway node has to translate messages from one protocol to another.

D. Reaction

Through inter-overlay links, traffic flows between cooperating networks and it directly affects both networks. Nodes react to changes in condition of physical and overlay networks caused by the cooperation and dynamically add, remove, or rewire links to have more preferable neighbors, i.e., a better network structure.

There are several strategies of such reactions [14], [16], [17], [18]. An overlay network normally employs a greedy and selfish strategy to maximize its own performance. In [16], they proposed a family of rules of link additions and defined classes of networks that emerged as a result. In [17], they considered random addition, random rewiring, and preferential rewiring as network modification algorithms. Both papers improve the robustness of networks, but they require the global and complete information about the network topology. Thus, we need to consider another modification algorithm, where a node does not need any global information and it can add, remove, and rewire connections on its own decisions.

E. Separation

The probability that gateway node j terminates an inter-overlay link is defined as $q_{w,j}$. If it is a constant, an inter-overlay link is disconnected at random even if it brings much benefit. On the contrary, when $q_{w,j}$ is defined as a utility function, for an inter-overlay link which is considered beneficial to a gateway node and/or its home network, $q_{w,j}$

becomes small. If a gateway node considers that it pays too much for the benefit, $q_{w,j}$ increases.

Depending on applications, we can consider other forms of symbiosis. The abovementioned strategy leads to mutualism, where both species benefit from each other. In commensalism, one species benefits from the other, but the other is unaffected. On the contrary, in parasitism, one species benefits from the other, but the other suffers.

III. Analysis of Evolving Overlay Network

To answer the first question raised in Section I, we first analyze characteristics of networks constructed by three different growth models by following the similar approach as in [19] and simulation experiments.

At each time step, a new node joins an overlay network. We do not consider disappearance of nodes. Nodes are numbered in the order that they join. The number of links that a new node establishes is m. The number of links that node i has at time t is denoted as $k(i,t)$. Consequently, the number of links in the network at time t is $S(t) = 2mt$. The number of nodes at time t is $N(t) = n_w(t) = t$. The probability distribution function $P(k,t)$ is defined for the ratio of nodes with degree k at time t.

BA is the model proposed by Barabási and Albert [9]. The probability that the n-th node established a link to node i with degree k_i is defined as $\Pi(k_i) = k_i / \sum_{j<n} k_j$. Therefore, the following partial differential equation holds.

$$\frac{\partial k(i,t)}{\partial t} = m\frac{k(i,t)}{S(t)} \quad (1)$$

$$= \frac{k(i,t)}{2t} \quad (2)$$

From Eq. (2) and the initial condition $k(i,i) = m$, we obtain,

$$k(i,t) = m(\frac{t}{i})^{\beta}, \quad \text{where } \beta = \frac{1}{2}. \quad (3)$$

In Fig. 2(a), a comparison with simulation results averaged over 10,000 trials is shown for the first node, where $m = 2$.

Next, the degree distribution at time t is defined as,

$$P(k,t) = \frac{1}{N(t)}|\frac{\partial k(i,t)}{\partial i}|^{-1}_{i:k(i,t)=k}. \quad (4)$$

From Eq. (3), we obtain,

$$\frac{\partial k(i,t)}{\partial i} = -\beta m t^{\beta} i^{-1-\beta}, \quad (5)$$

and the following holds for node i_k with degree k.

$$i_k = t k^{-\frac{1}{\beta}} m^{\frac{1}{\beta}} \quad (6)$$

By substituting i_k of Eq. (6) into Eq. (5) as i, we obtain,

$$|\frac{\partial k(i,t)}{\partial i}|_{i:k(i,t)=k} = \beta t^{-1} m^{-\frac{1}{\beta}} k^{1+\frac{1}{\beta}}. \quad (7)$$

Then, by substituting this and $N(t) = t$ into Eq. (4), a pdf of the degree becomes,

$$P(k,t) = \frac{1}{\beta} m^{\frac{1}{\beta}} k^{-1-\frac{1}{\beta}} \quad (8)$$

$$= 2m^2 k^{-3}, \quad (9)$$

which is the same as in [9]. A comparison with simulation results is shown in Fig. 3(a).

Next, we consider FR (Fully Random) model in which a new node randomly chooses m neighbor nodes. The rate of growth of the degree of node i can be expressed as,

$$\frac{\partial k(i,t)}{\partial t} = \frac{m}{N(t)}. \quad (10)$$

Then, we obtain the following result.

$$k(i,t) = m \log t - m \log i + m \quad (11)$$

For FR model, we have

$$\frac{\partial k(i,t)}{\partial i} = -\frac{m}{i}, \quad i_k = te^{1-\frac{k}{m}}. \quad (12)$$

Then,

$$|\frac{\partial k(i,t)}{\partial i}|_{i:k(i,t)=k} = mt^{-1}e^{-1+\frac{k}{m}}. \quad (13)$$

Finally, a pdf can be derived as,

$$P(k,t) = \frac{1}{2}e^{1-\frac{k}{2}} \quad (14)$$

Comparisons are shown in Figs. 2(b) and 3(b) for $m = 2$.

At last, we consider PR (Preferential and Random) model where a new node adopts the preferential attachment for αm links and the random attachment for $(1-\alpha)m$ links with $\alpha \in (0,1]$. First, the following partial differential equation can be derived.

$$\frac{\partial k(i,t)}{\partial t} = \alpha m \frac{k(i,t)}{S(t)} + (1-\alpha)m\frac{1}{N(t)} \quad (15)$$

$$= \frac{\alpha}{2t}k(i,t) + \frac{(1-\alpha)m}{t} \quad (16)$$

The solution of the equation becomes,

$$k(i,t) = \frac{(2-\alpha)m}{\alpha}(\frac{t}{i})^{\frac{\alpha}{2}} - \frac{(1-\alpha)2m}{\alpha}. \quad (17)$$

Then, items to solve Eq. (4) are derived as,

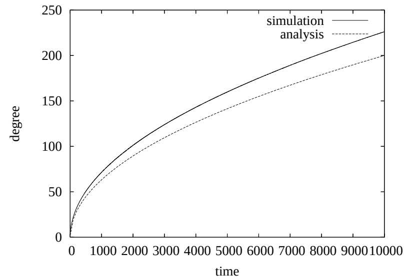
$$\frac{\partial k(i,t)}{\partial i} = -\frac{(2-\alpha)m}{2}t^{\frac{\alpha}{2}}i^{-\frac{\alpha+2}{2}}, \; i_k = \{\frac{(2-\alpha)m}{\alpha k + (1-\alpha)2m}\}^{\frac{2}{\alpha}}t. \quad (18)$$

Finally, we obtain a general form of a pdf for PR model as,

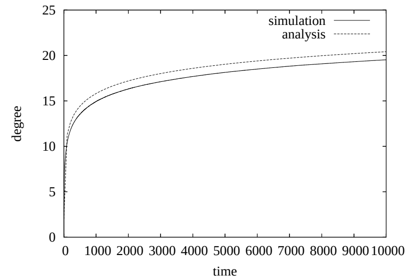
$$P(k,t) = \frac{2}{(2-\alpha)m}\{\frac{(2-\alpha)m}{\alpha k + (1-\alpha)2m}\}^{1+\frac{2}{\alpha}} \quad (19)$$

This implies that, first, for large k the degree distribution becomes $P(k,t) \sim k^{-1-\frac{2}{\alpha}}$ and, second, this trend appears earlier with larger α. Results illustrated in Figs. 2(c) and 3(c) for $m = 2$ and $\alpha = 0.5$ show good matches. In addition, the tail of the distribution shows the power-law feature with an exponential factor 5.

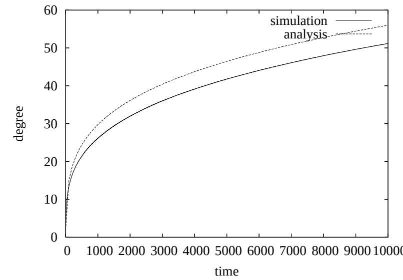
In addition to the above comparisons, we evaluated characteristics of generated networks from various viewpoints such as the clustering coefficient, the mean geodesic distance, the betweenness centrality, and the connectivity, while changing the number of new links m. Although figures and detailed discussion are omitted from the paper due to space limitation, for all of metrics, trajectories of PR model with $\alpha = \frac{1}{2}$ always lie between those of BA model and FR model.



(a) BA model

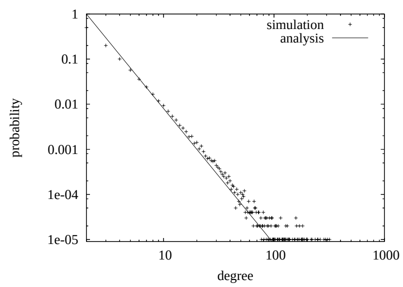


(b) FR model

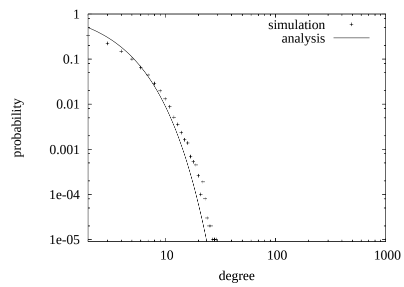


(c) PR model

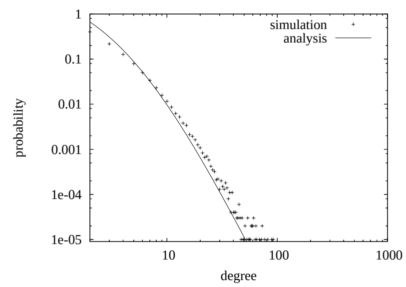
Fig. 2. Degree growth of the first node



(a) BA model

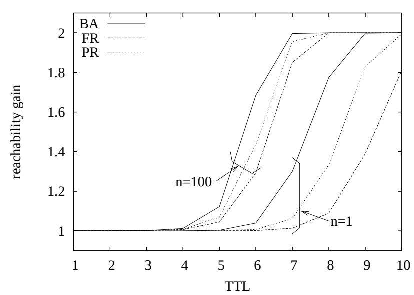


(b) FR model

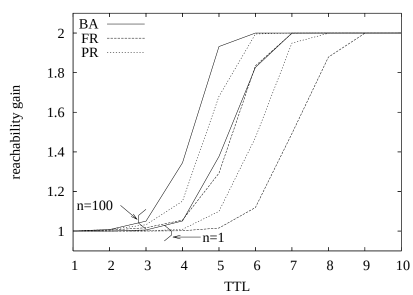


(c) PR model

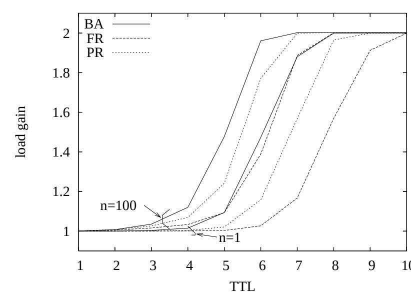
Fig. 3. Degree distribution



(a) Reachability gain: random



(b) Reachability gain: high-degree



(c) Load gain: high-degree

Fig. 4. Simulation results

IV. Evaluation of Cooperating Overlay Network

In this section, to see the influence of the growth models on the cooperation, we show some results obtained by simulation experiments on the effect of interconnecting two overlay networks. Two overlay networks of 5,000 nodes are generated by using BA, FR, or PR ($\alpha = \frac{1}{2}$) model. They are connected with each other by one or more inter-overlay logical links. Gateway nodes of the links are chosen at random, called ‘random connection’, or, in a descending order of degree, called ‘high-degree connection’.

In simulation experiments, each of 10,000 nodes generated a message and disseminated it over networks within a given TTL value by a flooding scheme. We evaluate obtained results in terms of the reachability gain and the load gain. The reachability is derived by dividing the average number of nodes that a message reaches by the total number of nodes, i.e., 10,000. The reachability gain is obtained by further dividing the reachability of a cooperative case by that of an independent case. The load gain is derived by dividing the number of messages involved in a cooperative case by that of an independent case. In [8], we evaluated the improvement of the robustness by cooperation by using the connectivity, i.e., the fraction of the size of the giant connected component to the number of remaining nodes after removing some nodes, as a metric and showed that even overlay networks of different applications or protocols also benefit from cooperation for enhanced robustness against failures of nodes.

In Figs. 4(a) and 4(b), results on the reachability gain are depicted. n in the figures corresponds to the number of inter-overlay links. Although we conducted simulation experiments with various settings of the number m of new links and the number n of inter-overlay links, only results with $m = 5$ and $n = 1$ and 100 are shown due to space limitation. By comparing two figures, we can see that the high-degree connection is more effective and efficient in increasing the reachability than the random connection. In both of figures, it is clear that overlay networks generated by BA model benefit the most from cooperation. For example, the result of $n = 1$ and TTL=7 in Fig. 4(b) means that a peer can find twice the number of providing peers, i.e., file holders in a decentralized-unstructured P2P file-sharing system by very loose cooperation with a single inter-overlay link. However, the benefit comes at the cost of increased load. In Fig. 4(c), the result of the load gain is depicted.

From figures in this section, we can conclude that an overlay network has to pay the cost, i.e., the increased load, in proportional to the benefit. Therefore, for efficient and effective cooperation, we need additional mechanisms to reduce the load on gateway nodes and networks such as proposed in [20], [15]. For example, it is shown that a gateway selection algorithm, where a node with higher degree becomes a gateway node at a higher probability and they are kept apart from each other, can successfully improve the application-level QoS without concentration of loads.

V. Conclusion

In this paper, we present the model of overlay network symbiosis where the symbiosis emerges from evolutions, interactions, and inner-transformation of overlay networks. However, as [6] revealed, the symbiosis does not always appear. To consider what kind of overlay network benefits from cooperation and what mechanism enables efficient and effective cooperation, we conducted some analytical and simulation experiments to investigate characteristics of evolving overlay networks and effect of cooperation.

As future works, we will give further detailed consideration on evolution, interaction, and inner-transformation of overlay networks to find conditions where the symbiosis emerges.

Acknowledgment

This research was partly supported by "New Information Technologies for Building a Networked Symbiosis Environment" in the 21st Century Center of Excellence Program and the Grant-in-Aid for Scientific Research (A) 18200004 of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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