On Socially-Inspired Cooperative and Efficient Overlay Network Evolution based on Group Selection Pattern

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ABSTRACT
In overlay networks, interplay between network structure and dynamics remains largely unexplored. In this paper, we study dynamic co-evolution between individual strategies (*cooperative* or *defect*) and overlay network structures. Inspired by evolutionary game theory, we propose a general scheme to evolve a given overlay into the resulting topology, which has *high global network efficiency* and *average clustering coefficient* that indicate high *small-world-ness*. In our scheme, peers' local interactions integrate network reciprocity and group selection algorithm, and lead to the emergence of cooperative and efficient overlay network structure. Specifically, we design a link-formation game to characterize the social dilemma of forming links in overlay network, which means that, in this game, defection always gives individual peers a higher payoff regardless of what opponent's strategy is, but, the aggregation of payoffs by mutual cooperative peers is always better than all other cases. In its evolutionary link formation phase, we adopt simple economic process−each peer keeps one link to cooperative neighbor in its neighborhood. Our simulation results show that the proposed mechanism can drive a given overlay network into fully cooperative and efficient small-world structure.

Keywords
Overlay network, evolutionary game, small-world network

1. INTRODUCTION
Overlay network is a virtual topology superposed on the current underlying infrastructure (the Internet) composed by autonomous and independent peers. The power of overlay network arises from the collaboration of its numerous constituent parts. If all the participating peers contribute some of their resources, for instance, bandwidth, memory or CPU cycles, highly scalable decentralized systems can be built which significantly outperform existing server based solutions. Unfortunately, in reality, many peers are selfish and strive to maximize their own utility by exploiting the system without contributing much themselves. A well-known mechanism designed to cope with the free-riding problem is the tit-for-tat policy, a kind of direct reciprocity [2], which is employed by the Peer-to-Peer (P2P) file-distribution tool, BitTorrent [3]. However, selfish behavior in overlay networks has numerous important implications even beyond the peer's unwillingness to contribute bandwidth or memory. For example, in unstructured P2P systems, a peer can select to which and to how many other peers in the network it wants to connect. On the other hand, recently, various network formation and growth models are proposed [1]. But, most of those existing approaches above are based on *growth rules* that depend on the instantaneous and full topological properties of the network, and neglect the co-evolution between network structure and individual rational behaviors.

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Increasingly, within biological and social science, modeling behaviors is expressed in the form of evolutionary algorithms. That is, individual entities such as cells, animals or human agents are represented as interacting, mutable and reproducing entities which are modeled computationally. Such models are typically co-evolutionary in nature in which the performance of individual entities is a result of some kind of interaction with the other evolving entities in the population. Such algorithm generally includes three phases: *interaction phase* specifies some rule by which entities interact (each agent has specific strategy, conducts some kinds of games with partner, like Prisoner Dilemma game or coordination game, etc [17]), and gain some reward (often termed utility); *reproduction (evolution) phase*: each agent differentially reproduces children based on its utility. The reproduction can be genetic (actually reproduce next generation) or cultural (entities are seen as behaviors or ideas that can replicate horizontally between peers within a generation); *mutation phase*: in the reproduction, with very small probability to change the strategy to incorporate innovation (that is, in the mutation, some peers bravely leave their current environment, and exploit the "new world"). The above interpretation of cultural reproduction gives us a clue as to how evolutionary models can be accommodated within overlay network structure evolution. Specifically, in our model of overlay network structure evolution, rewiring nodes or changing the topology of the network is a logical process in which nodes simply drop, copy or exchange symbolic links.

In this paper, we first design the link-formation game in overlay network to characterize the social dilemma of forming links in overlay network, which incorporates decisions of individuals when establishing new links or giving up existing links (that is, individual peer is capable of making rational choices). By social dilemma of forming links in overlay network it means that defection gives peers a higher payoff regardless of what opponent's strategy is. Therefore, if the game were to played only once by rational peers, who care only about their own material payoff, all peers would defect; on the other hand, the aggregation of payoffs by mutual cooperative peers is always better (larger) than all other cases. Then we analyze cooperative overlay network evolution by coupling the network formation rules with the dynamical states of the elements of the system. Specifically, we consider that peers of the network are individuals involved in a link-formation game and each peer preferentially links to the more suitable peer with higher utility and joins the latter's group (form the similar neighborhood view with the latter). In this way, the utility of a peer (biologically, *fitness*) is naturally the result of the dynamical evolution of the system, and, at the same time, the overlay can evolve from the arbitrary network structure into small-world network.

Briefly, the contribution of our paper is to combine the network reciprocity and group-based selection mechanism to simultaneously fulfill two goals: stimulate peers' cooperative behaviors, and evolve the overlay topology into small-world structure (*high global efficiency* and *average clustering coefficient*). More important, the above optimization acts at a local level since individuals search for their own benefit through conducting the link-formation game, rather than follows a global optimization scheme (that is, global properties emerge from peers' local simple interaction).

The paper is organized as follows: section 2 briefly introduced several related work, including network reciprocity, group selection, tag-based mechanism, and evolutionary preferential attachment, etc. The network group selection based topology evolutionary algorithm is proposed in section 3, which combines the network reciprocity and group selection mechanism, to evolve the arbitrary network structure into cooperative small-world network. Section 4 gives the simulation settings and analyzes the simulation results. Finally, we briefly conclude our paper and point out the future work.

2. RELATED WORK

Martin A. Nowak's seminal paper reviews five mechanisms for the evolution of cooperation: kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection. For each mechanism, a simple rule is derived that specifies whether natural selection can lead to cooperation [2]. We briefly introduce two mechanisms related to our work.

The basic model in [2] is that, in general, a cooperator is someone who pays a cost c, for another individual to receive a benefit, b. A defector pays no cost and does not distribute any benefit. In evolutionary biology, cost and benefit are metrics for fitness. Reproduction can be genetic or cultural. In the case of cultural reproduction, the strategy of someone who does well is imitated by others. Obviously, in an unstructured population, where all individuals are equally likely to interact with each other, defectors have a higher average payoff than unconditional cooperators. Therefore, natural selection increases the relative abundance of defectors and drives cooperators to extinction.

① Network reciprocity

Real world interactions are often restricted to small local group. Spatial structures or social networks imply that some individuals interact more often than others. One approach of capturing this effect is evolutionary graph theory, which allows us to study how spatial structure affects evolutionary and ecological dynamics. In this model, individuals occupy the vertices of a graph, and, the edges denote who interact with whom. Assume that the graph is fixed for the duration of the evolutionary dynamics. The fitness of an individual is given by a constant term, denoting the baseline fitness, plus the payoff that arises from the game. Ref. [5] studies the "death-birth" updating rule for evolutionary dynamics, that is, in each time step, a random individual is chosen to die, and the neighbors competed for the empty site proportional to their fitness. It is shown that evolutionary dynamic on graphs can favor operation over defection if the benefit to cost ratio, b/c, of the altruistic act exceeds the average connectivity k. Furthermore, the authors also explored "imitation" update mechanisms, that is, suppose at each time step, a random individual is chosen to update its strategy: it will stay with its own strategy or imitate one of the neighbors proportional to fitness. For this "imitation" updating, the result is that cooperators are favored if $b/c>k+2$.

In our paper, peer's interaction is constraint to its neighbors like the way in the network reciprocity, but, instead of assuming that the network graph is fixed for the duration of the evolution, the goal of reproduction phase is to try to find more suitable group of peers and to form close relationship with this group, and, finally to evolve the overlay network into efficient small-world structure.

② Group selection

Selection acts not only on individuals but also on groups. A group of cooperators might be more successful than a group of defectors. Generally, group selection refers to a process of natural selection that favors characteristics in individuals that increase the fitness of the group the individuals belong relative to other groups. A simple model of group selection works as follows: a population is subdivided into groups, which determines the interaction scope of the agents. Individuals reproduce proportional to their payoff, and offspring are added to the same group. If a group reaches a certain size, it can split into two with a certain probability p. In this case, a randomly selected group dies to constrain the total population size [6]. Note that only individuals reproduce, but selection emerges on two levels. In particular, pure cooperator groups grow faster than pure defector groups, whereas in any mixed group, defectors reproduce faster than cooperators. Therefore, selection on the lower level (within groups) favors defectors, whereas selection on the higher level (between groups) favors cooperators, then, under some conditions, groups performing well survive and groups with agents implementing poor coordination die out. The authors obtain that, if n is the maximum group size and m is the number of groups, then group selection allows evolution of cooperation, provided that $b/c>1+n/m$. In brief, group selection is a fully decentralized mechanism that focuses on the dynamic view of the groups, iteratively guides its evolution towards more optimal configurations.

In our paper, we use the peer's neighbor view as the group, and reproduction phase imitates the process that the fitter group attracts peers to join. And, furthermore, we explicitly investigate the evolution of overlay network structure based on peers' local interaction (link formation game).

③ Tag based model

Tag based model is the extension of group selection mechanism. Holland first proposed the concept of tags as markings or social cues that are attached to individuals (agents) and are observable by others [7]. These tags are often represented in computational models by a single number or a bit string, and they evolve like any other trait in a given evolutionary model. Ref. [8,9] proposed

SLAC (Selfish Link-based Adaptation for Cooperation) algorithm, which translates and applies the properties of Tag models to tackle cooperation issue in P2P systems. Here the concept of the tag is translated into nodes' neighborhoods - nodes therefore interact (in this paper, play a game) with other nodes they are directly connected to in the network. Each node generates a *utility* measure (u) according to some interaction with its neighbors. The higher the value of u, the better the node is performing. The algorithm is executed by each node and consists in it periodically comparing its own utility (say u_i) with another node (say u_j) randomly chosen from the network. If $u_i \le u_j$ then node i drops all of his current links and copies all j's links (and add a link to j itself) and j's strategy. Occasionally with low probability a node applies a "mutation" function after copying another node. This involves changing the strategy randomly and changing the links randomly. Those works argue that simple node-level "copy and rewire" policy, based on the tag dynamics, quickly eliminates free-riding between selfish nodes without centralized control. The process appears highly scalable and robust. Ref. [10] argue that, for tag based systems to support high levels of cooperation, tags must mutate faster than strategies, the reason is that cooperative tag groups need to spread (by mutation of tags) before free-riders (by mutation on strategies) invade the group.

Our work is a little similar to the tag-based model, but there exist the following differences: first, we focus on the evolution of overlay network structure and use a simple economic concept to facilitate the evolution of overlay network into small-world structure. Secondly, Ref. [10] neither analyzes the effect of ratio of benefit to cost on the evolution of cooperation nor investigate the effect of the evolutionary rule on the network efficiency, but our simulation results illustrate the following three different aspects: first, we show that, if there initially exist small percentage of cooperative peers in overlay network (it is most of real situations), mutation of strategy is not necessary for the evolution of cooperation (in our simulation, the initial percentage of cooperative peers is 0.1); second, under relatively large ratio of benefit to cost, mutation phase is also not necessary for the evolution of cooperation (but it can slightly speed up the convergence of cooperation), and reversely, mutation phase has negative effect on the characteristics of small-world network (decrease the global efficiency of overlay network); finally, in peer's evolution phase, keeping several links to cooperative peers in its original neighborhood view, can slightly speed up the convergence of cooperation and increase the global efficiency with negligible cost of decreasing of clustering coefficient.

④ Evolutionary preferential attachment

The interplay between the local structure of the network and the hierarchical organization of cooperation is highly complex. Ref. [11] studied network growth and formation by proposing an evolutionary preferential attachment model, its main feature being that the capacity of a node to attract new links depends on a dynamical variable governed in turn by the node interactions. The authors consider that the nodes of the network are individuals involved in a social dilemma and that newcomers are preferentially linked to nodes with high fitness, the latter being proportional to the payoffs obtained in the game. In this way, the fitness of an agent is not imposed as an external constraint, but rather it is the result of the dynamical evolution of the system. At the same time, the network is not exogenously imposed as a starting point, but instead it grows from a small seed and acquires its structure during its formation process. The evolutionary preferential attachment mechanism points to an evolutionary origin of scale-free networks and may help understand similar feedback problems in the dynamics of complex networks by appropriately choosing the game describing the interaction of nodes. We posit that our proposal in this paper is general framework for the evolution of overlay network structure, based on peers' simple local interaction. That is, when other reproduction rule is properly designed, then the overlay network can be evolved into other network structure, like scale-free network, etc, which will be investigated in our future work.

3. NETWORK GROUP SELECTION BASED OVERLAY TOPOLOGY EVOLUTION

We propose an evolutionary mechanism for overlay network topology based on network group selection, which can drive overlay network composed by autonomous and rational peers into a cooperative small-world network structure, based on relatively simple local interactions among peers. The basic model is given as follows: considering a population of N peers consisting of cooperative and defect peers, initially, peers form connections randomly. A cooperative peer helps neighbors, like forwarding packets for its neighbors or answering queries for its neighbors, etc. For the formed link that connects any two peers (cooperative or defect), we assume that, without loss of generality, the cooperative behavior brings cooperator cost δ (for its partner will exploit the cooperative peer), and bring its partner the benefit, 1. The defect peer faces no cost, for it will not use resource to provide any service for its partner. Therefore, we design the following link-formation game (shown in Table 1). Note that, for the link formation game to be meaningful, δ should be less than one. Even though the link-formation game is extremely simple, it still captures the intrinsic dilemma of link formation in overlay network. That is, defection gives peers a higher payoff regardless of what opponent's strategy is. Therefore, if the game were to be played only once by rational peers, who care only about their own material payoff, all peers would defect; on the other hand, the aggregation of payoffs by mutual cooperative peers is always better (larger) than all the other cases. Note that, although, the format of elemental link formation game by two neighbors is similar to the traditional Prisoner Dilemma (PD) game, considering that this game is conducted by each peer with its all neighbors, thus, the final utility for each peer is different from the utility in traditional PD game conducted by two agents.

The more complex Bilateral Connection Game (BCG) is proposed in [15,16] to characterize the topology formed by selfish peers, in which each peer attempts to minimize its cost in the network (the cost includes two components: the cost of the number of connections that each peer establishes with other peers, as well as the sum of the costs of reaching all other peers). But our link formation game is significantly different from the above work. For, generally, it is very difficult for each peer to evaluate its utility (or cost) based on global network topology (in BCG). Instead, in our scheme, each peer can simply utilize local information such as a partial view of the overlay structure and local interaction with neighbors to obtain its utility, which is more feasible for each peer in large-scale and dynamic P2P systems.

Furthermore, Ref. [15,16] adopt Nash equilibrium to characterize the stable properties of P2P network, but our work stems from evolutionary game, and focuses on the property of emergence and the structural features of overlay networks.

Table 1 Payoff table in link formation game by two neighbors

	Cooperative(C)	Defect (D)
Cooperative (C)	(1- δ, 1- δ)	(-δ, 1)
Defect (D)	(1,-δ)	(0, 0)

The above link formation game by two neighbors implies that:

If peer i is cooperative, peer i's utility in the formed overlay network graph G is: $u_i(G) = (1-\delta)n_i^c(G) - \delta n_i^{nc}(G) = n_i^c(g) - \delta n_i(G)$;

If peer i is non-cooperative, then its utility is: $n_i^c(G)$, where $n_i(G)$, $n_i^c(G)$ and $n_i^{nc}(G)$ respectively represent the number of peer i's total neighbors, peer i's cooperative neighbors and peer i's non-cooperative neighbors in the formed overlay network structure G.

Fig. 1 shows the outline of our proposed overlay topology evolution algorithm. In this algorithm, peers are randomly bootstrapped into an arbitrary network structure at the beginning. Then, the following three phases (interaction, evolution and mutation) are then executed:

① Interaction phase: the link-formation game is applied inside each peer's neighborhood view (group), and utility is correspondingly collected for each peer;

② Evolutionary phase: provided the condition for evolution is met (success in finding peer in more proper group), the peer migrates to groups hosting outperforming peers (copy the suitable peer's link structure and add an extra link to the peer). In evolutionary phase, we explicitly forbid peer i from changing its current neighborhood view (group) in the case of not finding a suitable peer in the overlay network, and peer i just skips operation in this round and goes directly to mutation phase. Furthermore, considering that, in real network, each peer only maintains limited links to its neighbors, thus, we constrain that peer i randomly selects (*maximum*-1) links from peer j's neighbors (plus the formed link to j) to guarantee the formed links by peer i no more than specific maximum number, *maximum*, which implies that the average degree of the formed overlay network is almost *maximum*. In the following simulations, we set *maximum* equals 10.

③ Mutation phase is implemented simply as the creation of a brand new group by peer i abandoning its current group, and randomly selecting a peer to form link. Other peers can migrate to this seed group in the future and grow the group size as a result. Note that we mutate just neighborhood view (corresponding to Tag in tag-base model) and do not introduce mutation in strategies (cooperative or defect), which is unnecessary for the emergence of cooperation/coordination, when there exist small percentage of cooperative peers at the initial stage. Furthermore, note that our simulation result shows, under relatively large ratio of benefit to cost (1/δ), mutation phase is also not necessary for the emergence of whole cooperative network, which complies with the result offered in Nowak's work [2,5]. Although, mutation phase can slightly speed up the convergence of cooperation, but it has negative effect on the global efficiency of overlay network (shown Fig. 8 in the following section).

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Bootstrap peers in arbitrary overlay network structure
LOOP for a number of rounds
    LOOP for each peer i in overlay network
        According to peer i's neighborhood view (group), obtain the utility u_i through playing the above link-formation game; (Table 1) (Interaction phase)
    ENDLOOP
    LOOP for each peer i in the overlay network (Evolution phase)
        Select a random peer j from the overlay network;
        IF u_i≤u_j
            Copy strategy from j;
            Drop peer i's all original links, except one link pointing to cooperative peer (if have);
            Randomly select and add links to peer j's neighbors, and add an extra link to j (guarantee the total formed links by peer i no more than specific maximum);
        ENDIF
        Mutate: with small mutation probability, drop i's link structure (abandon peer i's current neighborhood view), and add a link to a random peer. (Mutation phase)
    ENDLOOP
ENDLOOP
```

Fig. 1 The outline of overlay topology evolution algorithm

Interestingly, in an autonomous overlay network, the link formation is pair-wise, which means that two peers should be mutually consent in the formation of a link connecting those two peers [13]. Thus, intuitively, if each peer wants to form link with another peer, the former should persuade the latter to accept this connection. Therefore, based on the simple economic consideration, in peer's evolutionary phase, the peer will keep the link (if any) to one cooperative node in his original neighborhood view (illustrated in Fig. 2), which will facilitate the evolution of small-world overlay network structure (shown in the following simulation results). All the above aspects significantly differ our work from tag-based model, especially works conducted by Hale [8~10].

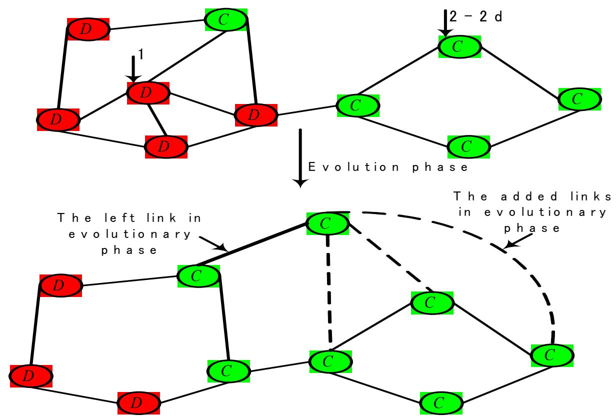

Fig. 2 The illustration of evolution phase in network group selection mechanism

Fig. 2 graphically illustrates the evolution phase of our proposed algorithm. The red point marked with "*D*" represents the defect peer, and the green point marked with "*C*" denotes the cooperative peer. According to the link-formation game, the designated defect peer's utility is 1 (for it only connects to one cooperative peer), and this peer compares with the cooperative peer shown in the upper part of Fig. 2. If the term (2-2δ) exceeds one, then the designated defect peer will copy the designated cooperative peer's strategy and link structure, and add an extra link to the right peer. Thus, the structure evolves into the graph shown in the lower part of Fig. 2. Note that, in Fig. 2, the thick line denotes the left link in the evolutionary phase, and three dotted lines represent the added links in the evolutionary phase.

4. MEASUREMENTS AND SIMULATION RESULTS

4.1 Measurements

In the subsection, we use the following three metrics to measure our scheme's performance and illustrate the structural characteristics of the finally formed overlay network.

① Percentage of cooperative peers in overlay network: after each round, we compute the ratio of cooperative peers to the whole nodes in overlay network to show whether our proposal can drive the overlay network into whole cooperative status.

Traditionally, the characteristic path length (that is, the average of the shortest path length between two any peers in network) is used to describe one of the distinguished features of "small- world" network. But, this measurement can only be applied to fully connected network graph (that is, there exist at least one path between two any peers), and can not characterize the network graph composed by several isolated components. Thus, we use the general metric, network efficiency *E* (a quality introduced in [14]), to measure how efficiently network *G* exchanges information. The global efficiency is a good measure of the performance of parallel systems. Such a variable is based on the assumption that the information/communication in a network travels along the shortest routes and that the efficiency $\varepsilon(G,j,k)$ in the communication between two points *j* and *k* is equal to the inverse of the shortest path length $d(G,j,k)$, that is, the efficiency of *G* is the average of $\varepsilon(G,j,k)$:

② $$E(G)=\frac{1}{N(N-1)}\sum_{j\neq k\in G}\varepsilon(G,j,k)=\frac{1}{N(N-1)}\sum_{j\neq k\in G}\frac{1}{d(G,j,k)}$$

The quantity $E(G)$ is perfectly defined in the case of non-connected graphs, in fact when there is no path between two point *j* and *k*, we assume $d(G,j,k)=+\infty$, and consistently $\varepsilon(G,j,k)=0$.

Average clustering coefficient: Watts and Strogatz propose to calculate the so-called clustering coefficient *C* in small-world network. First of all, a quantity C_i, the local clustering coefficient of node *i*, is defined as:

$$C_i=\frac{\text{Number of edges in } G_i}{\text{Maximum possbile number of edges in } G_i}=\frac{\text{Number of edges in } G_i}{k_i(k_i-1)/2}$$

where G_i is the subgraph of neighbors of *i*, which is composed of peer *i*'s all direct neighbors, and links among those neighbors, and k_i is the number of neighbors of peer *i*. Then at most $k_i(k_i-1)/2$ edges can exist in G_i, this occurring when the subgraph G_i is completely connected (every neighbor of *i* is connected to every other neighbor of *i*). C_i denotes the fraction of these allowable edges that actually exist, and the clustering coefficient $C(G)$ of graph *G* is defined as the average of C_i over all the vertices *i* of *G*:

③ $$C(G)=\frac{1}{N}\sum_{i\in G}C_i$$

4.2 Simulation results

This subsection comprises two parts of experimental results. One is the effect of various parameters (the value of delta δ, mutation probability and the number of left peers in evolution phase) in our algorithm on the cooperation convergence. In this part, we use the metric of percentage of cooperative peers. Another is to characterize the structure properties which appear in our overlay topology evolution scheme. In this part, we adopt measurements of global efficiency and average clustering coefficient. Note that we programmed the simulations so that, on average, over one round, each peer executes the evolution phase for one time. And, in those experiments, when the overlay networks get into full cooperative, the simulations will stop.

① Cooperation convergence study

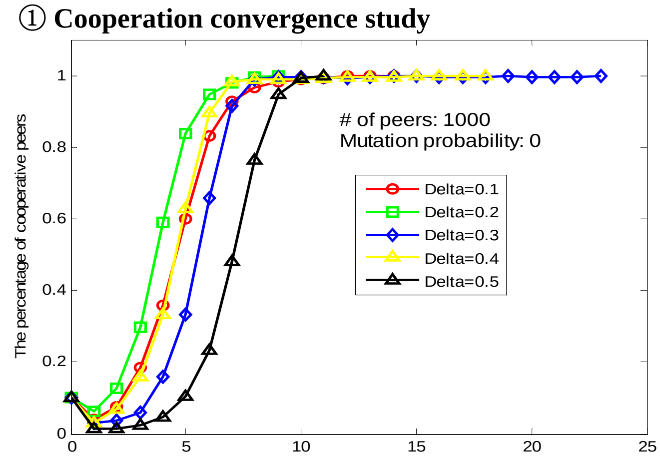

Fig. 3 Cooperation evolution under small value of delta (peer number: 1000 & no mutation)

The results in Fig. 3 illustrate that, under small delta value corresponding to relatively large ratio of benefit to cost (delta from 0.1 to 0.5 in our experiments), mutation phase is not necessary for reaching the full cooperative status (mutation probability 0 means no mutation on the evolution phase). Our further experiments also show that, when the value of delta is relatively large, without mutation phase, our proposal can not converge to the full cooperative status.

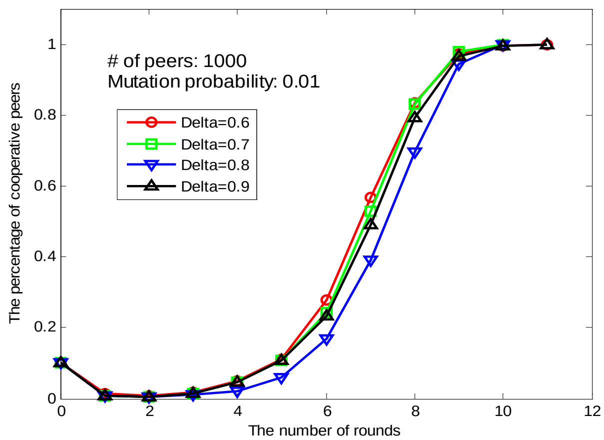

Fig. 4 Cooperation evolution under large delta value (peer number: 1000 & mutation probability 0.01)

In order to achieve convergence under large delta value, as shown in Fig. 4, mutation phase is needed, that is, in reproduction, with small probability, each peer drops its original group (neighborhood view), and randomly selects one peer to connect. In biological sense, mutation means that some peers bravely exploit the "new world", which enhance the probability of forming cooperative group, and in turn, facilitate the evolution of cooperation.

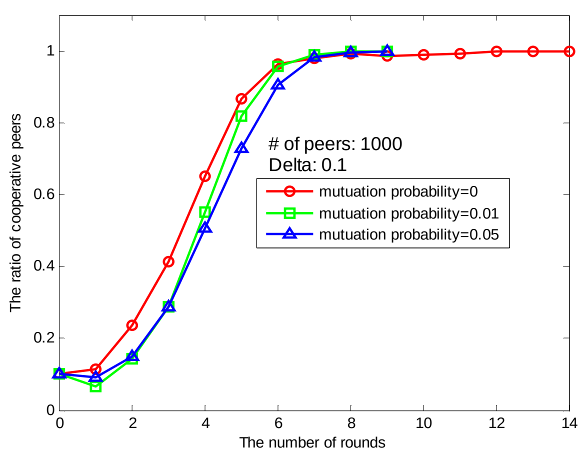

Fig. 5 The effect of mutation probability on cooperation evolution (under small delta value)

In order to determine, under small value of delta, whether the mutation probability has great effect on the cooperation evolution or not, we conduct the experiments of cooperation evolution under different mutation probability (Delta always equals 0.1, the left number of peers in evolution phase is constant 1). Fig. 5 implies that, under small value of delta, the mutations phase is not necessarily needed for evolving the overlay network into cooperative status, which complies with the results in Nowak's work [2,5] (In their seminal work for network reciprocity, the ratio of benefit to cost larger than average connectivity will favor the cooperation evolution. Note that the average degree of our simulated network will be almost 10, thus, the selection of delta 0.1 roughly complies with their result). But as Fig. 5 shows, mutation phase slightly speeds up the cooperation convergence.

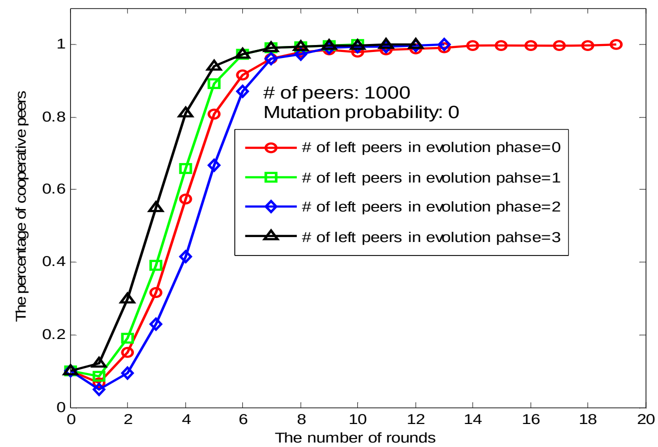

Fig. 6 The effect of different number of left peers in evolution phase on cooperation evolution

In order to achieve the small-world structure in our proposed evolution mechanism, we keep several links to the cooperative peers in peer's original neighborhood view (group). Fig. 6 illustrates the effect of different number of left peers on the evolution of cooperation. The result shows that keeping one or two links connecting to cooperative peers in original group can slightly speed up the cooperation convergence. More importantly, keeping one or two links in evolution phase can greatly improve the global efficiency of overlay network (will be shown in Fig. 7 and Fig. 8).

② Small-world structure study

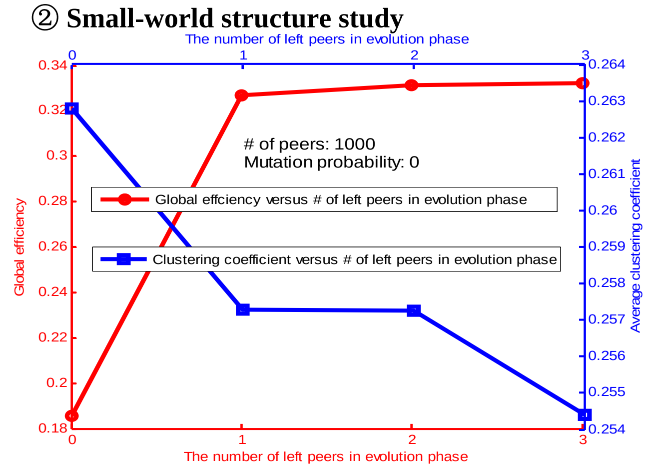

Fig. 7 The effect of the number of left peers on global efficiency & the clustering coefficient

In the evolution phase of our algorithm, when the peer joins the more attractive group, several links to the cooperative peers in its original neighborhood view will be kept. Fig. 7 shows the effect of the number of left (kept) peers in evolution phase on the global efficiency $E(G)$, and average clustering coefficient $C(G)$ in the same figure. The left and bottom axes (the red curve with circle) denote the global efficiency and the right and upper axes (the blue curve with square) represent the average clustering coefficient. As the number of left peers increases, the global efficiency increase, but average clustering coefficient decreases. Furthermore, the number of left peers larger than one only brings slight change to global efficiency and average clustering coefficient, which is the main reason why we select the number of left peers in evolution phase as 1 in most experiments.

Note that, It is reported that the typical value of clustering coefficient in Internet is from 0.18 to 0.30 [1]. Ref. [14] also shows that, global efficiency in social network and Internet are 0.37 and 0.29 respectively. Considering that, P2P can be regarded as a special kind of social network superposed on Internet, thus, from Fig. 7, we can posit that our scheme does evolve the overlay networks into efficient small-world structure.

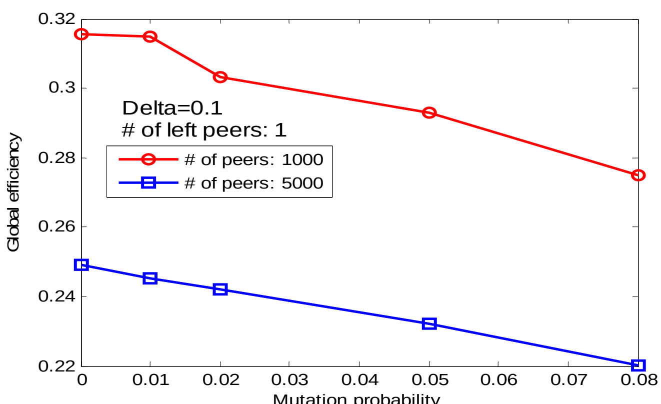

Fig. 8 The effect of mutation probability on global efficiency (peer number 1000 & 5000)

Fig. 4 shows that, when delta is relatively large, it is necessary to adopt mutation phase to guarantee the convergence of cooperation evolution, but, mutation phase have negatively effect on the network efficiency. As shown in Fig. 8, as mutation probability increases, the global efficiency of network gradually decreases. The intuitive reason lies in that, in mutation phase, some peers leave from their original groups, and randomly form link to another peer, which normally increases the shortest distance from those peers to others, and even enhances the probability of forming isolated subgroup. For example, in Fig. 3, for mutation probability 0 (no mutation), the corresponding characteristic path length is almost 3.5. But, for the mutation probability 0.02, there exist some isolated components in the formed overlay network, therefore, the distance from peers outside this component is infinite, which degrades the total network efficiency. We also conduct a great deal of similar experiments with different parameters, which illustrate the similar result.

4.3 Discussion

In brief, our proposed overlay topology evolution mechanism based on network group selection can drive the whole overlay network into full cooperative status. Furthermore, when the ratio of benefit to cost ($1/\delta$) is relatively large (correspondingly, δ is relatively small), mutation phase is unnecessary for cooperation evolution, but if the ratio is relatively small, then mutation phase is needed. The full cooperative overlay network can be achieved, although it may do well for a while, a very selfish peer will tend to lose neighbors as they (those neighbors) find other nodes that are members of more cooperative groups and hence have higher utilities. Additionally, selfish nodes doing well (exploiting neighbors) are a signal for other peers to imitate them and exploit their neighbors—killing the defect cluster quickly. Most importantly, our proposal achieves the goal of evolving the overlay network into efficient small-world structure (high global efficiency and average clustering coefficient). And, the mutation probability has negative effect on the networking efficiency and clustering coefficient, that is, with the increasing of mutation probability, the global efficiency gradually decreases. Finally, we also show that the simple economic consideration (keeping several links to the cooperative peers in original group) will greatly improve the network efficiency (with the trade of the slight decreasing of clustering coefficient), furthermore, we also show one left peer can achieve good performance.

Note that our proposed scheme can be viewed as a "*self-organized*" evolution of overlay networks: "The basic mechanism underlying *self-organization* is the noise driven variation which explores different regions in a system's state space until it enters an attractor" [4]. For our paper's case, the state space consists of all cooperative and defect peers in the system with various linking structure. The noise results from network reciprocity and group selection mechanism. The attractor is the cooperative small-world network structure. Our paper also meets a set of conditions targeting scalability and practical issues: being simple to implement in real systems, not imposing computation or other expensive requirements on peers and not requiring central coordination component.

5. CONCLUSIONS

Traditional systems tend to be rigid in structure, but the overlay network is free form and flexible in structure, that is, the autonomous peers determine the structure, and it evolves continually. In this paper, we present a cooperative overlay network topology evolution model based on the combination of network reciprocity and group selection mechanism, in which the rules governing the evolution of the network are linked to the dynamics of its components. In this model, peers are capable of making rational choices to establish new links or give up existing links, represented as a link-formation game. Furthermore, peers can simply compare their utility with nodes in other groups (neighborhood views) and move to them if they appear to be doing better, and meanwhile, copy better peer's strategy and join its group. We also adopt a simple economic concept to keep one link to the cooperative peer in the peer's original group, which can greatly improve the network efficiency and slightly increase the convergence speed of cooperation evolution.

Note that this optimization acts at a local level since individual peer searches its own benefit rather than following a global optimization scheme. Interestingly, the above simple local interaction leads to a cooperative and efficient network structure, i.e., a small-world network structure (high network efficiency and average clustering coefficient). Our evolutionary mechanism for overlay network structure is extremely simple and incurs little computational cost, respecting the rational behavior of each peer and enabling high scalability.

Since our work presented in this paper is still preliminary, we intend to extend this work in the following aspects.

① Implicit assumption of our mechanism is that peers are capable of finding some peers and comparing utility with them, thus the resulting problems are: how to find other peers and why other peers should reveal their neighborhood view and their strategies to those unknown peers (that is, incentive mechanism). Naturally, economic models may need to incorporate behavioral aspects of each peer in overlay network.
② This paper conducts experiments to investigate the effect of various parameters (mutation probability, the left number of peers and the ratio of benefit to cost) on the cooperation evolution, the global efficiency and average clustering coefficient, respectively, and draw some initial results. But, it is imperative to theoretically investigate the way to select appropriate parameters for the best performance, and the phase transition caused by different δ value and mutation probability.
③ We posit that our proposal is a general framework for the evolution of overlay network structure, based on peers' simple local interactions. That is, when other reproduction rule is properly designed, the overlay network can be evolved into other network structure, like scale-free network, etc, which will be investigated in future work.

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