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An efficient strategy for enhancing traffic capacity by removing links in scale-free networks

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Abstract. An efficient link-removal strategy, called the variance-of-neighbor-degree-reduction (VNDR) strategy, for enhancing the traffic capacity of scale-free networks is proposed in this paper. The VNDR strategy, which considers the important role of hub nodes, balances the amounts of packets routed from each node to the node's neighbors. Compared against the outcomes of strategies that remove links among hub nodes, our results show that the traffic capacity can be greatly enhanced, especially under the shortest path routing strategy. It is also found that the average transport time is effectively reduced by using the VNDR strategy only under the shortest path routing strategy.

Keywords: network dynamics, random graphs, networks, traffic models

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Contents

1. Introduction

Traffic processes have attracted great attention in recent years due to the immense increase of traffic in practical communication systems (see articles [1]–[11] and references therein). A few typical examples are air traffic between cities, packet flows on the Internet and power flows on power grids etc. The performance of these systems will be substantially degraded when they are put into heavy traffic conditions. The traffic problem has thus gradually become a topic of theoretical interest in the area of applied physics.

Recently, it was found that many practical systems such as airport systems, the Internet, power grids, etc, exhibit typical network structure. Small-world [12] and scale-free [13] characteristics are two of the most important ones in these network structures. Recent studies have proposed some models for mimicking traffic routing on complex networks [5], [14]–[18] by introducing packet generation rates and randomly selected sources and destinations for each packet. In the past few years, taking into account the underlying network structure, much effort has been dedicated to enhancing traffic capacity to improve the transport efficiency of packets on networks. Some studies focused on finding efficient routing strategies. These strategies, which are regarded as 'soft' strategies because they do not require any topological changes in the network structure, route packets in different ways. For example, in [15], packets are always routed along their topological shortest paths; in [19], packets are forwarded to non-central nodes using an efficient method. In [20, 21], the authors used static topological information and dynamic traffic information to enhance traffic capacity. In [22], local and global topological ingredients are integrated to enhance traffic capacity. In [23], the authors proposed an algorithm that can balance traffic on a network by minimizing the maximal node betweenness with as little path lengthening as possible. All these 'soft' strategies were proved to be efficient in improving transport efficiency.

To improve transport efficiency, there are different strategies for changing network topology. These strategies are usually regarded as 'hard' strategies. Investigations of optimal network structure for alleviating congestion in communication networks are useful for guiding the designing of communication networks and have become important problems in the field of network traffic. For example, in [16], by rewiring links in networks, the authors found that a star-like configuration was optimal when packets were routed in a

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network with a low packet generation rate; a homogeneous–isotropic configuration was optimal when packets were routed in the network with a high packet generation rate. But due to the high costs, it is usually difficult to add new links or rewire existing links in a network. Removing links in a network, however, is much easier to implement at low cost. For example, in air traffic network, ideally one can remove links by forbidding certain air traffic movements between certain cities. On the Internet, one needs only to remove the connections among computers through computer software. In fact, the link-removal strategy has been extensively studied to enhance or optimize traffic dynamics of different kinds. In [24], the authors pointed out that the removals of nodes or links could alleviate or even mitigate cascades of overloading on networks. In [25], the link-removal strategy was applied in the metabolic network. They pointed out that the removals of metabolic reactions, which represent links in the metabolic network, could improve metabolic performances and rescue defective metabolic networks. In [26], the authors found that the removals of links could also help to enhance synchronization in complex networks of dynamical systems. Literature studies on enhancing transport capacity by removing links in communication networks have also been reported. Recently, in [27], the authors proposed a high-degree-first (HDF) strategy. The HDF strategy is able to effectively enhance the traffic capacity by removing certain links among hub nodes (i.e. the nodes with high degrees) in scale-free networks. They argued that if there were fewer links among hub nodes, packets would make detours round the hub nodes, thus enhancing the traffic capacity. Likewise, in [28], the authors proposed the high-betweenness-first (HBF) strategy which is also able to enhance traffic capacity by removing links among the nodes with high betweenness.

In this paper, we find that using the strategies of [27, 28] to identify the links to be removed in scale-free networks is far from optimal, which means that the strategies described in [27, 28] can be further improved. On the basis of the optimization results which are obtained by using the SA (simulated annealing) algorithm [34, 35], we propose a link-removal strategy. This new strategy not only considers the important role of hub nodes, but also balances the amount of packets from each node to its neighbors by reducing the variances of neighbors' degrees of some nodes. In this paper, we call our strategy the variance-of-neighbor-degree-reduction (VNDR) strategy, for short. We carry out the VNDR strategy under the shortest path routing strategy and local routing strategy [29] in scale-free networks. Simulation results reveal that the performances of the VNDR strategy are superior to those of HDF and HBF strategies, especially under the shortest path routing strategy.

This paper is organized as follows. In section 2, we describe the scale-free network model, the routing strategies and some background about traffic problems. In section 3, we detail the implementation of the SA algorithm to search for optimal results. The presentation of the link-removal strategy will then follow. In section 4, we show the simulation results obtained using the proposed strategy, followed by comparative analysis and discussions. Finally, conclusions are drawn in section 5.

2. Model description and some notation

Our study is performed on scale-free networks generated from the well known Barabási–Albert (BA) scale-free network model, in which the degree distribution follows a power law $p(k) \sim k^{-\gamma}$ (γ is the degree exponent). This model is able to imitate many communication networks with heterogeneous network structures, such as the Internet AS level topology [30, 31], the topology of unstructured P2P distributed systems [33], etc. The model incorporates two important mechanisms: growth and preferential attachment. When forming a scale-free network, it begins with an initial network with m_0 ($m_0 \geq 2$) nodes. It is noted that all nodes should be in one component, i.e. there is at least one path between any two nodes of a network. At each time step, a new node is added to the network and then is connected to m ($m \leq m_0$) existing nodes. The probability of a new node being connected with an existing node i is $p_i = k_i / \sum_j k_j$, where k_j is the degree of node j, and j runs over all existing nodes. Duplicate links between any two nodes are strictly forbidden. The generation process terminates when the predefined number of nodes is reached. In this paper, the parameters are set at $m_0 = 3$ and $m = 3$.

For simplicity, all nodes in a network are equally considered as hosts and routers for generating and delivering packets. Packets are generated with a given rate ρ at randomly selected nodes at each time step. Each packet is designated with a randomly chosen node, different from its source node, as the destination to which the packet will be delivered. Packets are routed in the network in parallel following a given routing strategy. We assume that each node can forward only one packet to other nodes at each time step. The queue length of each node is assumed to be unlimited and the principle of FIFO (first in, first out) is applied at each queue [17]. Finally, a packet will be removed from the network once it reaches its destination.

The shortest path routing strategy and local routing strategy [29] are adopted to route packets in this study. The shortest path routing strategy is widely adopted in practical communication networks. A typical example is the Internet, in which packets are transported almost along shortest paths both within domains and between domains [28, 32]. In the shortest path routing strategy, each packet is routed along the shortest path between the source and destination. Unlike in the shortest path routing strategy in which each packet has the global information about network topologies, the local routing strategy assumes that global information about network topologies is unavailable to each packet transported in the network. In the local routing strategy, a packet is directly routed to its destination if the packet's destination is one of the direct neighbors of the searching node. Otherwise, the packet will be forwarded to node i, one of the direct neighbors of the searching node, with probability

$$\Pi_i = \frac{k_i^{\alpha}}{\sum_j k_j^{\alpha}}, \tag{1}$$

where the sum runs over all direct neighbors of the searching node, k_i is the degree of node i, and α is a tunable parameter for controlling the routing of packets in the network.

In this study, we are interested in the traffic capacity, measured by the critical packet generation rate ρ_{c}. The critical rate ρ_{c} is a crucial parameter determining how packet transportation behaves around a steady value. When the packet generation rate, ρ, is lower than the critical packet generation rate ρ_{c}, the number of packet loads in the network fluctuates around a steady value. The network system undergoes a phase transition at $\rho = \rho_{\mathrm{c}}$ to a congested phase, in which the number of overall packet loads diverges. We use the order parameter introduced in [4] to describe the critical packet generation rate

$$\eta(\rho) = \lim_{t \to \infty} \frac{\langle \Delta W \rangle}{\rho N \Delta t}, \tag{2}$$

where $\langle \Delta W \rangle = W(t + \Delta t) - W(t)$ and $\langle \cdots \rangle$ is the average over time windows of width Δt. $W(t)$ is denoted as the number of packets in the network at time step t and N is the network size. When $\rho < \rho_c$, $\Delta W = 0$ and $\eta = 0$, it indicates that the network system is under the congestion-free state.

3. Method description

This section will firstly detail the optimization process using the SA algorithm to search for the optimal results. We will then describe our proposed VNDR link-removal strategy. It should be noted that the shortest path routing strategy is used together with the SA algorithm to route the packets. The objective of using the SA algorithm is to search the links whose removals are most beneficial for enhancing transport capacity. Then we can summarize the characteristics of the removed links and then establish our link-removal strategy. Assuming in a scale-free network G with N nodes, we require removing L links to maximize the traffic capacity ρ_c. Using the SA algorithm, the whole process is carried out as follows.

(i) First, at temperature $T = T_0$, the L links are randomly selected but all the nodes have to be in one component after removing the L links. The traffic capacity ρ_c of the network with the L links removed is then evaluated. Note that the capacity ρ_c is regarded as the optimal rate ρ_{copt} and the network with the L links removed is regarded as the optimal network G_{opt} at the beginning.

(ii) Randomly recover one of the L links and remove one of the other existing links in the network G_{opt}. Evaluate the traffic capacity ρ'_c of the new network G'. Then compare ρ'_c and ρ_{copt}. If $\rho'_c < \rho_{copt}$, then with probability $\exp(-(\rho_{copt} - \rho'_c)/T)$, the network G' is accepted as the optimal network G_{opt} and we set $\rho_{copt} = \rho'_c$. Otherwise, if $\rho'_c \geq \rho_{copt}$, then with probability 1, the network G' is accepted as the optimal network G_{opt} and $\rho_{copt} = \rho'_c$.

(iii) Repeat step (ii) M times and decrease the temperature by $\varepsilon\%$.

(iv) Iteratively implement step (iii) until the predefined temperature T_f is reached.

After completing the optimization process, the optimal network G_{opt} and its traffic capacity ρ_{copt} are derived. Compare the optimal network G_{opt} with the initial network G; it is easy to find which links are removed from the initial network G. We find that the removed links are not always within hub nodes. Each of these links is connected to a hub node at one end and a low-degree node at the other.

Actually, from our optimization results, it is considered that the distribution of neighbors' degrees of a central node can heavily affect the flow of packets from the central node. We use figure 1 to elaborate on this conjecture. In figures 1(a) and(b), we show the uneven and even distributions of neighbors' degrees around the central node P, respectively. In the case of an uneven distribution, if there is a packet located on the central node P at some step, the packet is very likely to be forwarded to the node with degree $k_D = 10$ at the next time step under the shortest path routing strategy. This is mainly due to the fact that nodes with high degrees provide more paths from the central node to other nodes. Therefore, node D is more likely to become congested. In contrast, in figure 1(b), since the neighbors' degrees of the central node are identical,

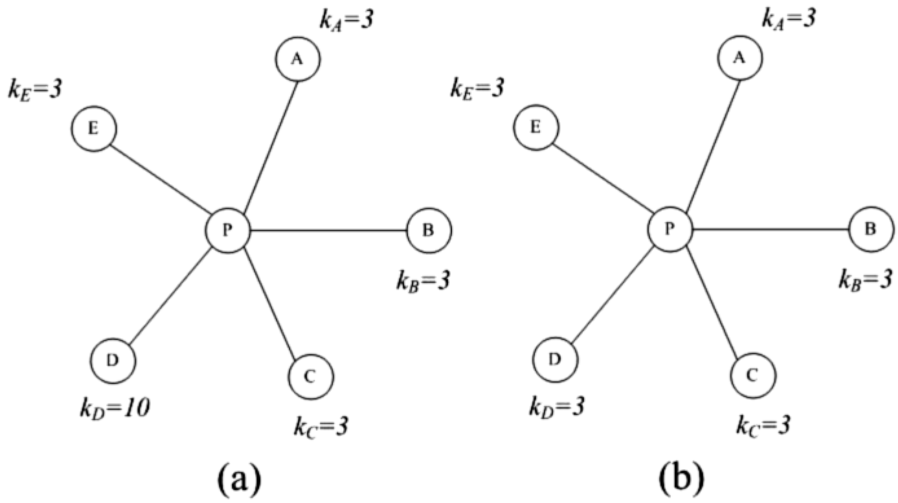

Figure 1. Illustration of uneven (a) and even (b) distributions of neighbor degrees for a central node. Node P is the central node and nodes A, B, C, D and E are five neighbors of node P. k_i is the degree of node i.

there is no obvious indication that packets on the central node are forwarded to certain neighbor. Packets are disseminated approximately evenly to neighbors A, B, C, D and E from the central node P. This scenario is undoubtedly beneficial in alleviating congestion in communication networks.

Formally, for node i, if the relative variance of neighbors' degrees (RVND), defined as

$$\mathrm{rvar}(i) = \frac{\mathrm{std}_{j\in \mathrm{nei}(i)}(d(j))}{(1/|\mathrm{nei}(i)|)\sum_{j\in \mathrm{nei}(i)} d(j)}, \tag{3}$$

is large ($\mathrm{nei}(i)$ is the neighborhood set of node i), then packets are more likely to be routed to hub nodes under the shortest path routing strategy. In equation (3),

$$\mathrm{std}_{j\in \mathrm{nei}(i)}(d(j)) = \sqrt{\frac{(d(j) - (1/|\mathrm{nei}(i)|)\sum_{j\in \mathrm{nei}(i)} d(j))^2}{|\mathrm{nei}(i)| - 1}}. \tag{4}$$

Hence, the hubs nodes are more likely to be congested. If the link between the hub node and the node with high RVND is removed, for example the link between node P and node D is removed in the left figure of figure 1, the distribution of neighbor degrees for the node with high RVND will become more even and therefore traffic amounts are balanced in the network. Finally, the traffic capacity is enhanced.

In the light of the analysis above and the role of hub nodes, we propose the VNDR link-removal strategy to enhance traffic capacity in scale-free networks. For each node i in the initial network G, we define

$$H(i) = \mathrm{rvar}(i) \times \mathrm{std}_{j\in \mathrm{nei}(i)}(d(j)) \times d(i). \tag{5}$$

We choose the node p_1 with the maximal value of H. Choose the node q_1 with the highest degree from the neighborhood set of node p_1. Remove the link connecting node p_1 and node q_1. Then a new network G_2 is generated. For the network G_2, we re-compute H for all nodes and choose nodes p_2 and q_2 in the same way. The whole link-removal process is repeated until a predefined fraction f_c of the links are removed. We note that all nodes have to be in one component in the whole process. If the removal of a link causes certain nodes to be disconnected from the original network, we will not remove the link. Instead, we go on to deal with the link that connects the node p with the variable H ranked next and the node q with the highest degree in the neighborhood set of node p.

4. Simulation results and relevant discussion

We shall evaluate the performance of the VNDR strategy by comparing it with the high-degree-first strategy [27] and the high-betweenness-first strategy [28]. We investigate the critical packet generation rate ρ_c. The average shortest path length is L_{ave}, also reported, and all results are averaged over 100 different network realizations. In conducting the SA search, the initial and final temperatures are set at 10 and 10^{-4} respectively. The temperature decreasing coefficient is set at $\varepsilon\% = 0.99$.

For simplicity, the fraction of removed links is denoted as f_r. The results for ρ_c and L_{ave} versus f_r obtained under the shortest path routing strategy are shown in figure 2. For comparative analysis, the results from the VNDR strategy, HDF strategy, HBF strategy and SA algorithm are all illustrated. Irrespective of the link-removal strategy used, with the increasing of the fraction of removed links, ρ_c is always first increased to a certain value, until $f_c \approx 0.3$, and then decreased. This is natural because when the fraction of removed links is below 0.3, packets are diverted from hub nodes to non-central nodes and therefore loads are balanced on the nodes of the network. As a result, the traffic capacity is enhanced. But when the fraction of removed links exceeds 0.3, the number of routing lines is significantly reduced and packets have to travel along long paths to arrive at their destinations. As a result, packets are likely to be accumulated in the network and the traffic capacity is reduced.

More importantly, it is found that the performance of the VNDR strategy is superior to those of the HDF and HBF link-removal strategies in enhancing traffic capacity. Under our VNDR strategy, traffic capacity is enhanced more rapidly with the increasing of the fraction of removed links compared with the cases for the HDF and HBF strategies. Using our strategy, fewer links have to be moved to acquire the same traffic capacity as using HDF and HBF strategies. This means that the VNDR strategy is more economical. On the other hand, we find that the maximal traffic capacity is also substantially enhanced under the VNDR link-removal strategy. For the case of network size $N = 1000$, the maximal traffic capacity approaches $\rho_c = 0.05$ using the VNDR strategy. In contrast, the maximal value of ρ_c is only around 0.035 using the HDF strategy and around 0.03 using the HBF strategy. The case of $N = 500$ also validates the superiority of the VNDR strategy over the HDF and HBF strategies. As we have stated, the SA algorithm searches for the links whose removals are the most beneficial for enhancing traffic capacity. We observe that the traffic capacity after removing links using the VNDR strategy is close to that obtained using the SA algorithm. The results show that the VNDR link-removal strategy is efficient for enhancing the traffic capacity under the shortest path routing strategy.

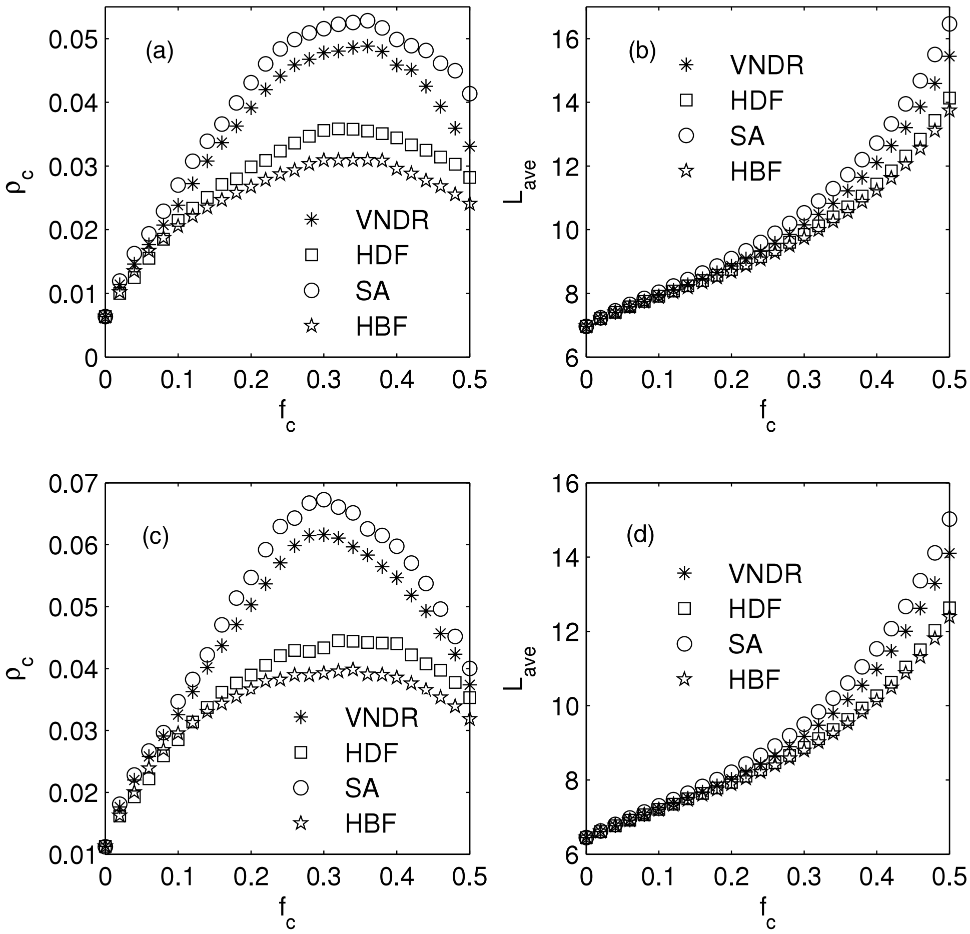

Figure 2. Illustration of ρ_c and L_{ave} versus f_c under the shortest path routing strategy. Network sizes are set at $N = 1000$ in (a) and (b) and $N = 500$ in (c) and (d).

It is worth noting that the superiority of the VNDR strategy over the HDF and HBF strategies in enhancing the traffic capacity can be rationalized. In HDF or HBF strategies, the links among hub nodes are always the first to be removed. On the other hand, it is well known for scale-free networks that there are only a few hub nodes and the degrees of most other nodes are rather low [13]. Thus, HDF and HBF strategies are supposed to be efficient only in the first few link-removal iterations. When all links among hub nodes are removed, the removals of other links among non-hub nodes can hardly enhance the traffic capacity with the same efficiency as the link removals among hub nodes achieved in the first few iterations. But the VNDR strategy focuses only on the uneven distributions of neighbor degrees. Thus, compared to HDF and HBF strategies, the high efficiency of VNDR can persist for more iterations. Figure 2 validates our viewpoint. In figure 2, it is shown that the performances of the VNDR strategy, HDF strategy and HBF strategy deviate only slightly from each other at the beginning of the link-removal iterations, i.e. when $f_c < 0.1$. But it is clear that when $f_c > 0.1$, the traffic capacities are significantly enhanced using the VNDR strategy compared to using the HDF and HBF strategies.

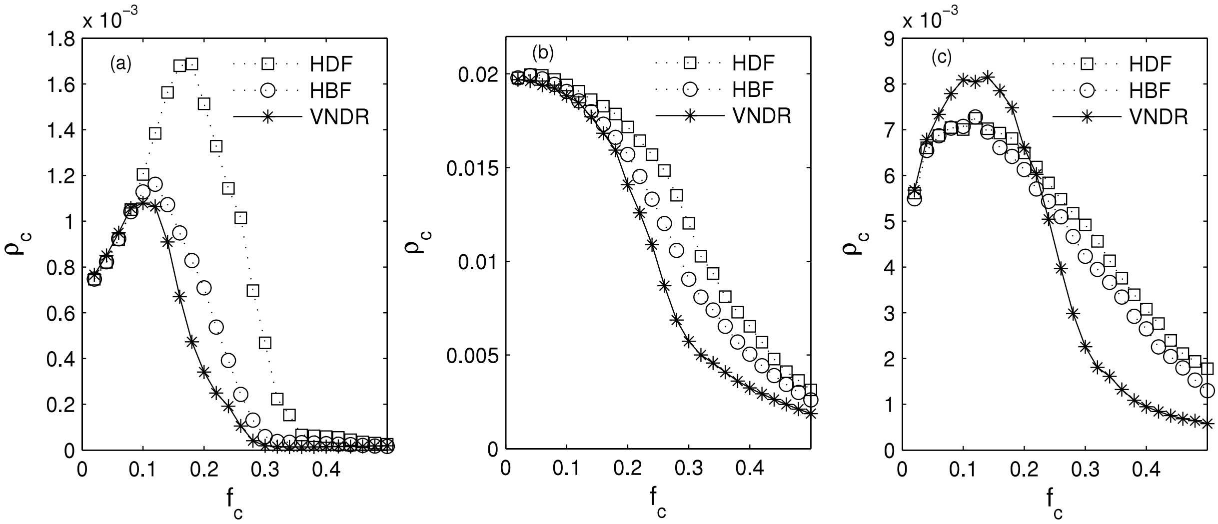

Figure 3. Illustration of ρ_c versus f_c under the local routing strategy. The network size is set at $N = 1000$ in all figures. The routing parameter α is set at -4, -1 and 1.5 in (a), (b) and (c) respectively.

The average shortest path length L_{ave} versus the fraction of removed links f_r is reported in figures 2(b) and (d). It is not surprising that L_{ave} increases monotonically when the fraction of removed links gradually increases. This is because the removals of links can cut the existing shortest paths, and the path between any two distinct nodes may become lengthened. We find that when the fraction of removed links does not exceed 0.3, L_{ave} derived from the VNDR strategy deviates a little from those derived from HDF and HBF strategies. This result reveals that, compared to HDF and HBF strategies, the VNDR link-removal strategy can effectively enhance traffic capacity without substantially lengthening the average shortest paths.

Next, we shall investigate the performance of the VNDR strategy under the local routing strategy. The traffic capacities using the HDF strategy, HBF strategy and VNDR strategy under the local routing strategy are shown in figure 3. We set the routing parameter α at three different values, -4, -1 and 1.5. The results show that the network capacity always reduces with the increasing of f_r in the case of $\alpha = -1$ irrespective of the link-removal strategy employed. This is because the distribution of packet loads on the nodes is the most uniform when $\alpha = -1$ [29]. Thus, the removals of any links cannot enhance the traffic capacity. In contrast, when α equals -4 or 1.5, the distribution of packet loads on the nodes is not so uniform as for the case of $\alpha = -1$. Regardless of the link-removal strategy used, the traffic capacity always first increases to a certain value and then decreases when the fraction of removed links increases. It is also noted that for the case of $\alpha = 1.5$, the maximal traffic capacity, achieved at $f_c \approx 0.1$ for all link-removal strategies, is further enhanced using the VNDR strategy compared to HDF and HBF strategies. But the performance of our strategy is inferior to those obtained by using HDF and HBF strategies for the case of $\alpha = -4$. The different behaviors of the performances of our strategy are attributed to the routing characteristics of packet loads. When $\alpha = 1.5$, packets are more likely to be forwarded to hub nodes. For any node

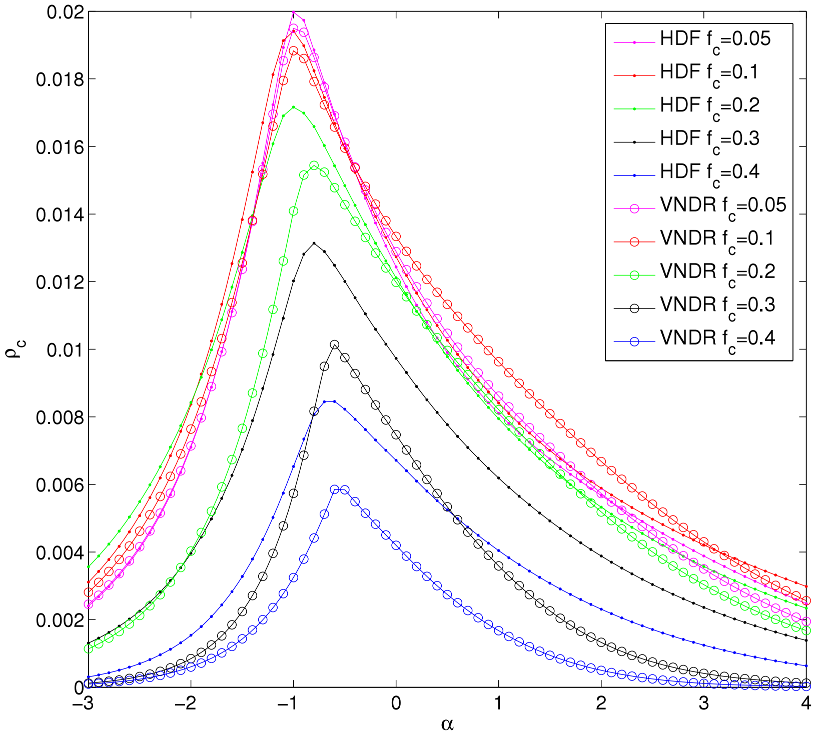

Figure 4. Illustration of $\rho_{\rm c}$ versus α under the local routing strategy for different settings of $f_{\rm c}$. The network size is set at $N = 1000$.

with high RVND, the link between the node and the node's neighbor with the highest degree is the path where packets are more likely to go through. Therefore removing such a link is beneficial for enhancing the traffic capacity. In contrast, when $\alpha = -4$, packets are more likely to be delivered to low-degree nodes. Therefore, for any node with high RVND, the links between the node and the node's neighbor with the low degrees are the paths where packets are more likely to go through. Thus, the VNDR link-removal strategy cannot further enhance the traffic capacity. To further evaluate the effect of α on the performance of the VNDR strategy, we illustrate the traffic capacity $\rho_{\rm c}$ with α varying from -3 to 4 using the VNDR strategy and HDF strategy in figure 4. We set the fractions of removed links $f_{\rm c}$ at 0.05, 0.1, 0.2, 0.3 and 0.4. It can be clearly observed that only when α lies in the range from 0 to 2 is the maximal capacity, achieved at $f_{\rm c} \approx 0.1$, further enhanced by using the VNDR strategy compared to the HDF strategy.

The average transport times $\langle T\rangle$ in the link-removal processes obtained by using the VNDR strategy and using the HDF strategy are investigated. The results under the shortest path routing strategy are illustrated in figure 5. At low values of the packet generation rate, the values of $\langle T\rangle$ obtained using the VNDR strategy and those obtained using the HDF strategy are found to be close to each other. On the other hand, at high values of the packet generation rate, it is clear that $\langle T\rangle$ will be significantly reduced by using the VNDR strategy compared to using the HDF strategy. This result indicates that under the shortest path routing strategy, as compared to the HDF strategy, the VNDR link-removal strategy can not only further enhance the traffic capacity, but also reduce

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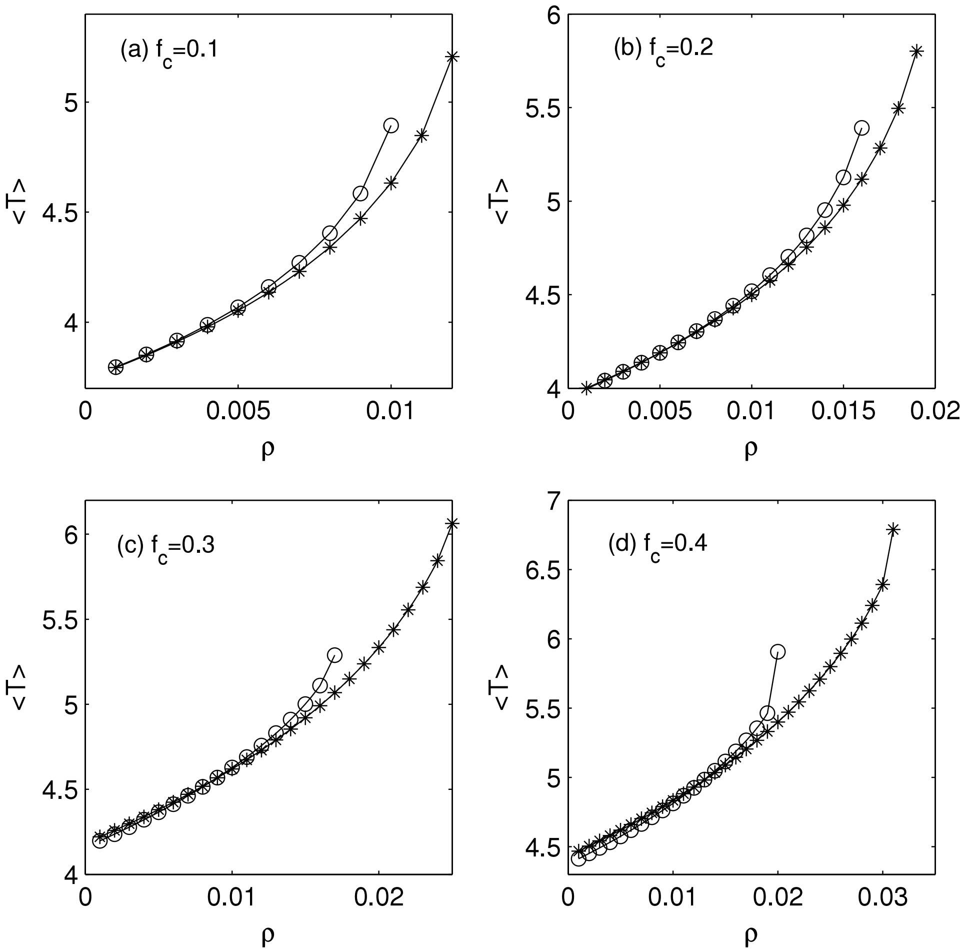

Figure 5. Average transport time $\langle T \rangle$ versus ρ for different values of f_c under the shortest path routing strategy. The network size is set at 1000 in all figures. The data are truncated at $\rho = \rho_\mathrm{c}$ above which $\langle T \rangle \to \infty$. In each figure, the results for the VNDR strategy and HDF strategy are marked with asterisks and circles. Solid lines are the guides for the eyes.

the average transport time. But under the local routing strategy, the transport times are generally lengthened by using the VNDR strategy compared to using the HDF strategy. When the value of α is in the region where the maximal traffic capacity can be enhanced, as shown in figure 6 for the case of $\alpha = 1.5$, it can be seen that, irrespective of the packet generation rate and the fraction of links that are removed, the transport time is still longer using the VNDR strategy than using the HDF strategy. This result indicates that under the local routing strategy, the VNDR strategy cannot supply a shorter average transport time compared to the HDF strategy.

5. Conclusion

We have proposed an efficient link-removal strategy, called the VNDR strategy, for enhancing traffic capacity by removing links in scale-free networks. This new strategy not

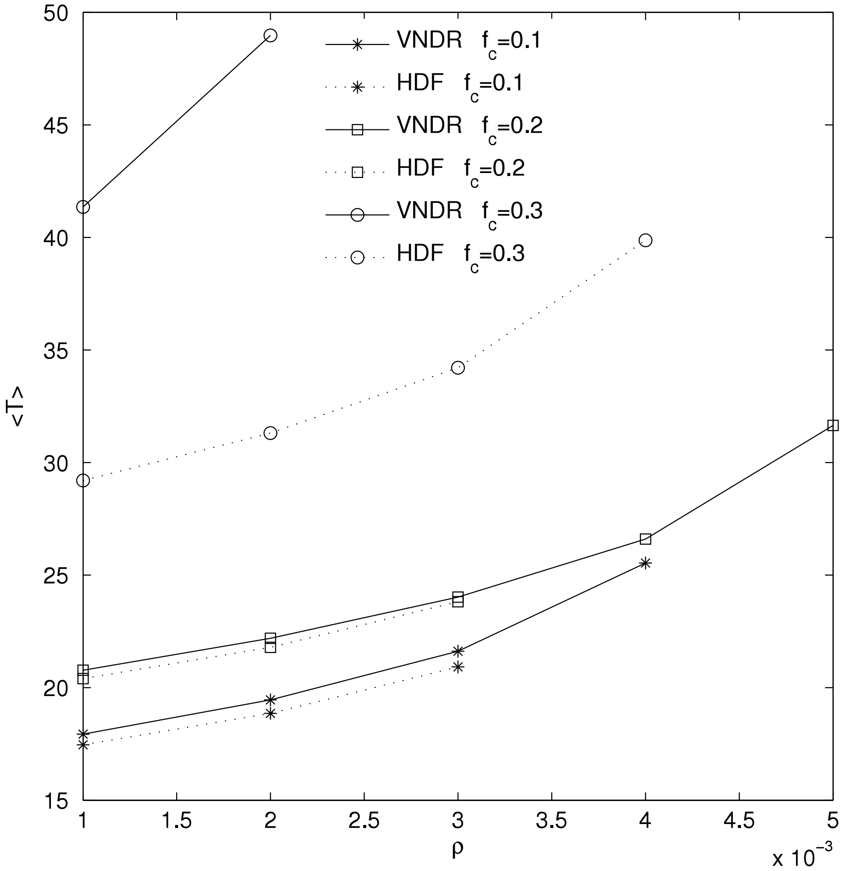

Figure 6. Average transport time $\langle T \rangle$ versus ρ for different values of f_c under the local routing strategy. The parameter α is set at 1.5. The network size is set at 1000. The data are truncated at $\rho = \rho_c$ above which $\langle T \rangle \to \infty$.

only considers the important role of hub nodes, but also balances the amount of packets from each node to the node's neighbors. Under the shortest path routing strategy, the VNDR strategy can further both enhance traffic capacity and shorten average transport time without substantially lengthening the average shortest path as compared to the high-degree-first and high-betweenness-first strategies. Under the local routing strategy, the VNDR strategy can achieve larger maximal traffic capacity when α lies in the range from 0 and 2.

The cost of removing links is low, and link removal can be easily implemented in practical communication networks because link removal can be achieved using software. In contrary, the cost is usually high for adding links or nodes to a given communication network. As the sizes of most practical communication networks will be consistently increasing in the foreseeable future, further investigation will be likely to focus on how nodes and links are to be added for enhancing traffic capacity.

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