Method to enhance traffic capacity for scale-free networks

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In this paper, a method is proposed to enhance the traffic handling capacity of scale-free networks by closing or cutting some links between some large-degree nodes, for both local routing strategy and global shortest-path routing strategy. The traffic capacity of networks is found to be considerably improved after applying the link-closing strategy, especially in the case of global routing. Due to the strongly improved network capacity, easy realization on networks, and low cost, the strategy may be useful for modern communication networks.

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Traffic flow is one of the most important processes involved in networks. The prototypes of traffic flow on networks are mass transfer by chemical reactions in a cell, packet transfer on the Internet, airplane traffic between airports, and so on. Since the discovery of small-world [1] and scale-free [2] phenomena, the properties of complex networks and the realization of free traffic flow on networks have attracted more and more attention from physicists [3–17].

Previously, traffic on networks has been extensively explored on regular or random graphs, and many valuable results have been found [11–13]. Recently, studies have been focused on developing better routing strategies in large complex networks to alleviate congestion and to improve efficiency of transportation [6]. Compared with the high cost of changing the infrastructure, developing a better route searching strategy is usually preferable to enhance the network capacity. Packets are suggested to be forwarded using different routing strategies, including the random walk [18,19], the shortest path [20,21], the efficient path [22], the nearest-neighbor and next-nearest-neighbor searching strategy [23–26], or the integration of static and dynamic information [25,27]. The traffic dynamics on networks have been successfully simulated with local or global information to minimize the packet delivery time or maximize the capacity of huge communication networks.

However, it has also been revealed that the traffic dynamics depend greatly on the topology of the underlying networks [7,11]. Guimerà *et al.* proved that homogeneous networks can bear more traffic because of the absence of high-betweenness nodes [13]. This conclusion is also demonstrated by systematic simulations of the traffic on scale-free and homogeneous networks [17]. In this light, this paper proposes a method to improve, by closing some key connections, the overall handling and delivery capacity of scale-free communication networks. This method is also inspired by congestion alleviation in highway traffic systems, in which some on ramps and/or off ramps are closed at rush hours. The strategy is carried out under both a local routing strategy [23] and global shortest-path routing strategy. It is found that the network capacity is effectively improved, particularly in the case of a global-information-based routing strategy.

The simulation starts by establishing the infrastructure of the network by adopting the well-known Barabási-Albert scale-free network model [3]. This model contains "growth" and the "preferential attachment" mechanisms: starting from m_0 nodes, one node with m links is attached at each time step in such a way that the probability Π_i of being connected to the existing node i is proportional to the degree k_i of that node, i.e., $\Pi_i = k_i/\Sigma_j k_j$, where j runs over all existing nodes. In this paper, the parameters are set to be $m_0=5$ and $m=5$ or 2, with network size $N=1000$ or 5000. For simplicity, all nodes are assumed to be both hosts and routers able to generate and deliver packets. At each time step, there are R packets generated in the system, with randomly chosen sources and destinations. The node capacity, that is, the number of data packets a node can forward to other nodes in each time step, is assumed to be a constant: $C=2$.

This paper considers the network traffic in the cases of both global and local routing strategies. Here "global" means that packets are forwarded following their shortest path from source to destination. In order to describe the phase transitions of traffic flow in the network accurately, we use the order parameter introduced by Arenas *et al.* [11]:

$$\eta(R) = \lim_{t\to\infty} \frac{C}{R} \frac{\langle \Delta N_p \rangle}{\Delta t}, \quad (1)$$

where $\Delta N_p = N(t+\Delta t) - N(t)$, $\langle \cdots \rangle$ indicates the average over time windows of width Δt, and $N_p(t)$ represents the number of data packets within the network at time t. With increasing packet generation rate R, there will be a critical value of R_c that characterizes the traffic phase transition from free flow to a congested state. For $R < R_c$, $\langle \Delta N_p \rangle = 0$ and $\eta = 0$, indicating that the system is in the free-flow state. However, for $R > R_c$, η increases rapidly from zero, and the system becomes seriously congested [21–26]. Therefore R_c is the maximal generating rate under which the system can maintain its normal and efficient functioning. Thus the overall capacity of the system can be measured by R_c.

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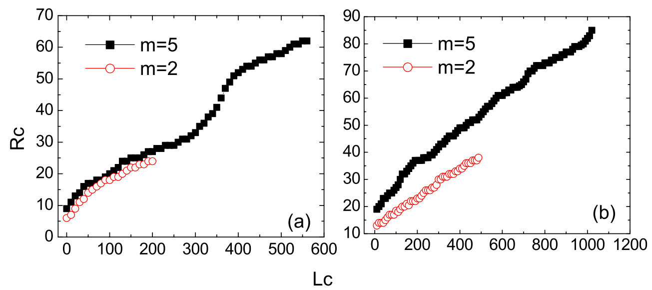

FIG. 1. (Color online) Critical R_c vs L_c under global routing strategy with network parameters (a) $N=1000$, $m=2$ and 5; (b) $N=5000$, $m=2$ and 5. The data are obtained by averaging R_c over ten network realizations.

The local routing strategy [23] can be described as follows. Each node performs a local search among its neighbors. If the packet's destination is found within the searched area, i.e., among the node's immediate neighbors, it is delivered directly to its target. Otherwise, it is forwarded to a neighbor node i, according to the preferential probability

$$P_i = \frac{k_i^\alpha}{\sum_j k_j^\alpha}, \tag{2}$$

where the sum runs over the neighboring nodes, k_i is the degree of node i, and α is an adjustable parameter to control the current target of a packet at each time step. Once a packet arrives at its destination, it will be removed from the system. The queue length of each node is assumed to be unlimited and the first-in first-out discipline is applied at each queue.

The link-closing method first rank the links according to the value of the product $(k_m \times k_n)$, where k_m and k_n are the links' end-node degrees. Then the links are closed according to this order from big to small. Because hub nodes are usually more important and bear more traffic load, the links with bigger values of $(k_m \times k_n)$ are easier to jam. Hence, closing or cutting some highly congested links can lead to the redistribution of traffic loads along links, so as to enhance the overall packet handling and delivering ability. As a remark, this paper uses the value of $(k_m \times k_n)$ instead of the links' betweenness centrality, which measures exactly the expected number of packages flowing through the link, because (a) it has been found that the betweenness centrality of links has strong correlation (almost linear) with $(k_m \times k_n)$ [28]; (b) in real weight networks, the weight of links (or traffic load) is proportional to the power of $(k_m \times k_n)$ [29]; (c) it is easier to rank the links by using the local information, since the calculation of betweenness centrality needs system-wide information.

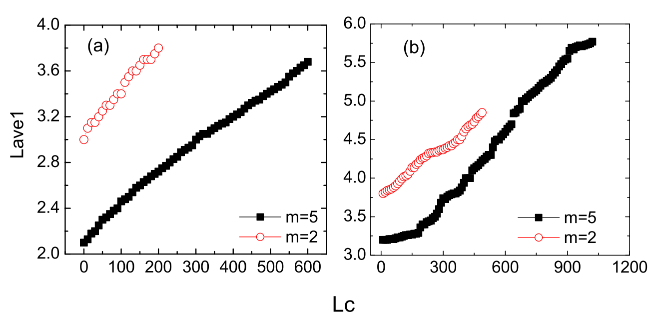

FIG. 2. (Color online) Average shortest path length L_{av1} vs L_c with network parameters (a) $N=1000$, $m=2$ and 5; (b) $N=5000$, $m=2$ and 5.

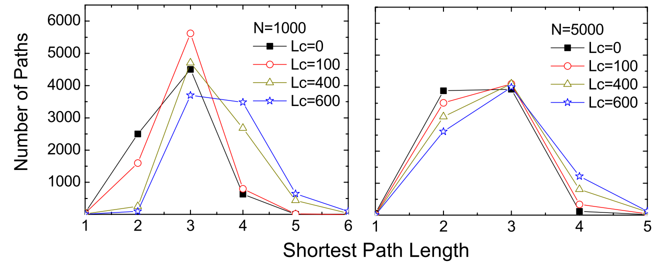

FIG. 3. (Color online) Distribution of shortest paths with different L_c links closed. Other network parameters are $m_0=m=5$.

For convenience, the number of closed links is denoted as L_c. The changes of some traffic properties, such as the system's overall capacity (R_c), average path length of the packet (L_{av}), and average traveling time ($\langle T \rangle$) are studied.

Figure 1(a) shows the increment of R_c versus L_c in the global shortest-path routing strategy. On closing the links according to the order of $(k_m \times k_n)$, R_c is a monotonically increasing function of L_c, which indicates that the maximal handling and delivering capacity of the system is remarkably enhanced. For $N=1000$ and $m=5$, R_c is enhanced from 10 to about 65 when L_c increase from 0 to 600. And for $N=1000$, $m=2$, R_c is enhanced from 5 to 24 when L_c increase from 0 to 200. In the simulation, when $N=1000$, $L=5000$ (L represents the number of links in the network), if $L_c>600$, some nodes become isolated and the connectivity of the network is broken, so that some packets cannot reach their destinations. Therefore, we stop closing the links. Figure 1(b) shows simulations on larger networks with $N=5000$, $m=2$ and 5. It also shows the same enhancement effect. These results demonstrate that the links-closing method is effective in enhancing the system's overall capacity.

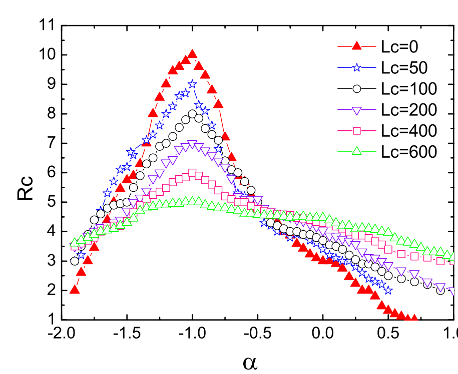

FIG. 4. (Color online) Critical R_c vs α with different L_c under the local routing strategy. The network parameters are $N=1000$, $m_0=m=5$, and $C=2$. The data are obtained by averaging R_c over ten network realizations.

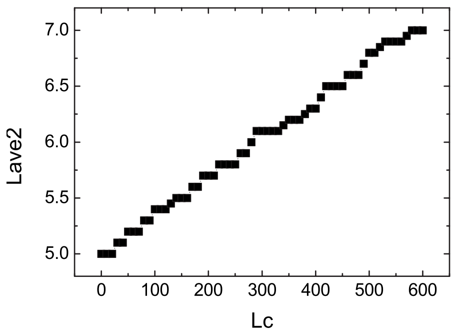

FIG. 5. Average path length L_{av2} vs L_c under the local routing strategy.

Next, we study the change of shortest path length affected by the cutting edge method. As shown in Fig. 2, the average shortest path length L_{av1} under the global routing strategy increases after cutting off links, and L_{av1} is a monotonically increasing function of L_c. It is not hard to explain the increment of L_{av1}. Initially, most packets tend to pass through hub routers. After some key links are cut off, the packets have to change their path to other routers that are not so heavily linked, and thus L_{av1} increases. Thus the link-closing method can enhance the overall traffic capacity, but at the cost of increasing the path length of the packets. Figure 3 shows the distribution of shortest paths for systems with $N=1000$ and 5000. One can see that, with increase of L_c, more paths will have longer lengths in both cases.

As a reference work, we investigate the behavior of R_c versus α for different L_c by using the local routing strategy. As shown in Fig. 4, the simulation results show that, when some links are cut off, the maximum value of R_c decreases with increase of L_c and the curves of R_c become smooth. When L_c increases from 0 to 600, the maximum value of R_c^{max} always emerges at $\alpha_c=-1.0$ as in [23], but its value decreases from 10 to 5. And as shown in Fig. 5, the average travel length L_{av2} increases with increase of L_c under the local routing strategy. It seems the link-closing method decreases the overall traffic efficiency. However, at the same time, the value of R_c become larger when α is far from -1.0. This implies that, after implementing our method, the network capacity is less sensitive to α. In fact, $\alpha_c=-1$ means that the packets are forwarded by avoiding the central node. The same effect is reached by closing the links around the central node, as in this work, so that α essentially has less effect on the traffic. Recently, it has been found for the local routing strategy that the optimal value of α greatly depends on link bandwidth [30], and the configuration of the packets' sources and destinations [31]. One can conclude that, after applying the link-closing strategy, the sacrifice in R_c^{max} may be worthwhile when the packets are not forwarded with a uniform α value or when the system has heterogeneity in the routing protocol. Thus this method can cause a packet-adaptive enhancement for network traffic.

Figure 6 shows the variation of average packet travel time $\langle T\rangle$ after applying the link-closing method under global and local routing strategies. One can see that $\langle T\rangle$ increases monotonically with R for both cases. $\langle T\rangle$ also increases more rapidly when more links have been closed, because the increment of the average path length makes packets spend more time on the network.

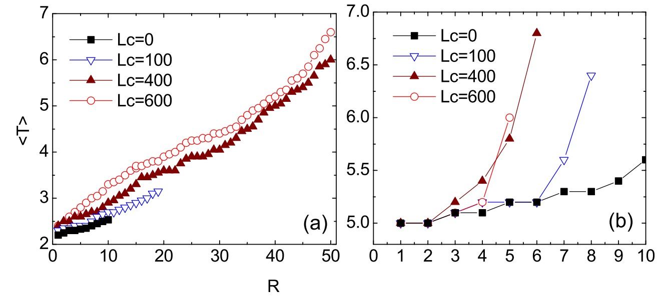

FIG. 6. (Color online) Average packet travel time $\langle T\rangle$ vs R for different L_c: (a) global routing strategy; (b) local routing strategy with $\alpha=-1.0$. The data are truncated at $R=R_c$ above which $\langle T\rangle \to \infty$.

In conclusion, this paper introduces an effective method to enhance the traffic capacity of scale-free networks by closing some key links at heavily loaded times. This method can evidently enhance the overall traffic handling ability of scale-free networks, especially under the condition of the global shortest-path routing strategy. For the local routing situation, the network's traffic capacity can be enhanced when the routing parameter α deviates from -1.0. Thus the link-closing method alleviates the sensitivity of the network capacity to α. Although the average path length L_{av} and average travel time $\langle T\rangle$ of packets will increase with the number of closed links, the method can help to achieve a system-optimal traffic capacity especially in global routing.

In Internet traffic, it has been found that there are some fluctuations in information flow [8]. So the link-closing method can be applied to alleviate traffic congestion at times of high flux, and the links can be recovered to decrease the travel time of packets at times of low flux. We note that this method can be easily implemented in real communication systems since the link closing and recovering can be achieved by software. To make sure the packets will be forwarded accurately after closing the links, a new routing table can be broadcast before closing the links, so that each router may modify its routing table and each packet can be forwarded by its new shortest path in global routing. For the local routing strategy, the routers only have to modify the information about neighboring nodes' degrees to ensure the accurate routing of packets. In this way, the network handling ability can be effectively enhanced without updating the routers' ability or links' bandwidth. So the cost of this method is very low.

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