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Effects of efficient edge rewiring strategies on network transport efficiency

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HIGHLIGHTS

- Three efficient edge rewiring strategies are discussed extensively to enhance the network efficiency.
- The effects of two routing strategies under different rewiring methods on network traffic capacity are done.
- This work provides new ways to improve network transport efficiency and can be incrementally used by network service providers.

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ABSTRACT

The transport efficiency of a network strongly depends on the underlying structure. The traffic capacity of one real network may be actually very small due to the heterogeneous degree distribution of the network under the global shortest path routing strategy. For the purpose of improving the traffic capacity of the network, in this paper, we propose three edge rewiring strategies. Extensive simulations under the efficient routing (ER) and the shortest path (SP) routing are applied to verify the effectiveness of the proposed edge rewiring mechanisms. It is found that the traffic capacity of the network can be substantially enhanced and the edge rewiring strategies are beneficial to the improvement of overall traffic handling and delivering ability of the network, especially under the SP routing strategy. The edge rewiring methods can be used incrementally to ameliorate the network transportation performance by network service providers.

1. Introduction

Many complex networks around us have the Small-World [1] phenomenon and Scale-Free [2] property, for example biological systems, highway networks, the Internet, WWW (World Wide Web) and so on. The research on the transport efficiency of complex networks has attracted a tremendous amount of interest and attention from the physics community and computer science. The ever-growing data transported on real networks motivates the study of high traffic capacity of current networks. Generally speaking, network congestion is caused by limited network resources or unreasonable resource distribution or scheduling mechanism. Two categories of ways to enhance network traffic capacity are improving the routing strategy and optimizing the network underlying infrastructure [3,4]. Due to the simplicity and low cost of the implementation of an efficient routing strategy, the former is often considered first, and has been studied extensively in recent years. Although finding the global optimal routing is an NP-complete problem [5], a number of heuristic routing strategies [6–26] are emerging, such as efficient routing (ER) [6], optimal routing (OR) [7,8], traffic-awareness routing

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(TAR) [9,10], local routing [11,12], global dynamic routing [13], and so on. These routing strategies have been confirmed to be efficient, and the traffic capacity of networks has been improved from several times to tens of times.

Although the implementation cost of modifying network structure is high, the study of effects of changing network structure on traffic capacity is essential for understanding traffic dynamics on complex systems. Optimizing network structure includes redistributing the whole network resources and altering the network underlying physical link connections. In real complex networks, the total resources are finite, such as the node's delivering capacity, the link's bandwidth, and the queue resource. With a homogeneous node delivering capacity distribution, real networks with heterogeneous degree distribution are easily congested under the widely used SP routing. Central nodes with the largest degrees or betweenness cannot deliver all packets on them immediately, and high packet loss rate or long packet transmission delay may occur. One direct way is to increase the delivering capacity of central nodes of the network [27]. With limited total node delivering capacity, one heuristic method is to efficiently reallocate each node's delivering capacity which is proportional to the node's degree or the betweenness centrality [28] and to the queue length of the node with an adjustable parameter [29]. Similarly, in the case of the finite total link bandwidth of one network, Ling et al. have proposed a conceptual bandwidth resource allocation strategy that each link's bandwidth is proportional to $(k_i k_j)^{\alpha}$, where k_i and k_j are degrees of node i and j respectively, and α is a tunable parameter [30]. In our previous works [31,32], we studied the betweenness based bandwidth allocation and global dynamic bandwidth allocation strategies.

Traffic capacity is highly related to the network structure on which traffic flows through Refs. [3,33,34]. Revising physical link connections of one network is also an alternative and efficient method to enhance the network transport efficiency. One economic strategy is to apply the link-directed method [35], in which directing a portion of heavily congested links under some direction-determining rules can redistribute traffic loads for congested links, thus improving the overall packet handling and delivering ability of the network. The link-directed method can be possibly implemented in some real complex systems such as communication networks by directing or recovering a proportion of links through software. Another interesting way to deal with the most congested links is the link-closing or link-removal method. Heuristically removing a fraction of links with heavy load can redistribute the traffic significantly, for example, removing such links with the largest $k_i * k_i$ or $B_i * B_j$ in Refs. [36,37] respectively, where B_i and B_j are the betweenness centrality of node i and j respectively. In Ref. [38], the authors used the simulated annealing (SA) algorithm to search for the most beneficial links whose removal influences transport efficiency most, and they found the distribution of neighbor degrees of a central node can strongly affect the flow of packets from central nodes. Therefore, they proposed a method called relative variance of neighbors' degrees (RVND) to further improve the link-closing strategies of Refs. [36,37]. Effectively adding links or nodes with links can definitely traffic capacity [39]. However, removing links will cause waste of the link resources of the network, and adding nodes and links will cause high cost of new elements. Meanwhile, to our knowledge, the research on rewiring physical link connections of network to increase the overall network traffic handling and delivering ability is neglected. In our previous work, we discussed some simple edge rewiring strategies and evaluated their effects on transport efficiency [40] and in this paper, we will further study the effects of different edge rewiring strategies on transport efficiency under different routing algorithms.

2. Models and edge rewiring strategies

Here we adopt one widely used traffic model. We regard each node as router and host. Every node can either generate packets or forward packets according the routing table. At each time step, there are R packets generated in the network, with each packet having randomly chosen source and destination. The queue length of each node is infinite and the first-in–first-out (FIFO) discipline is used for each queue. At each step each node can deliver at most C packets one step toward their destinations. Once each packet arrives at its destination, it will be removed from the system. Without loss of generality, here we set $C = 1$. The traffic capacity can be denoted by the critical packet generation rate R_c, at which the network undergoes a phase transition from free flow state to congested state. It can be described by the order parameter as in Ref. [34]

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

where $\langle \Delta W\rangle = W(t + \Delta t) - W(t)$ and $\langle \ldots \rangle$ notates the average over time windows of width Δt. $W(t)$ is denoted as the number of packets in the network at time t. When $R < R_c$, $\langle \Delta W\rangle = 0$ and $\eta = 0$, it means the network is under the free flow state. However, when $R > R_c$, $\eta > 0$, it indicates the number of packets in the network is increasing and the network is congested. Therefore, R_c is the maximal packet generation rate under which the network remains in the free flow state.

The widely used BA (Barabási–Albert) [2] scale-free networks are employed to model real networks such as telecommunication networks. The construction of a BA scale-free network is as follows. Starting from m_0 fully connected nodes, at each step, a new node with $m(m \le m_0)$ edges is added to the existing network, and the other end of each new edge is chosen preferentially according to the probability $\Pi_i = \frac{k_i}{\sum_j k_j}$, where k_i is the degree of node i and j runs over all existing nodes in the network. It has been found that due to the homogeneous distribution of the node's delivering capacity and the heterogeneous degree distribution of scale-free networks, the traffic capacity is evidently small when compared with homogeneous networks such as two-dimensional lattice networks [6]. As shown in Fig. 1, the traffic capacity of two-dimensional lattices is at least ten times more than that of BA scale-free networks.