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Optimization of network traffic

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Abstract— **A network traffic system can be tuned by three factors: (i) the topology of underlying infrastructure; (ii) the distribution of traffic resources; (iii) the routing strategy. In this paper, we propose a model to study the optimization of network capacity based on complex network theory. We study the optimization method of network traffic in several situations corresponding to the real cases. The model is proposed mainly for the information traffic system. It can also be modified to characterize the behavior of an urban traffic system. Our study can benefit the modern communication networks, urban transportation systems, airline traffic, and power grids.**

I. INTRODUCTION

Complex networks can describe many natural and social systems. Since the discovery of small-world phenomenon [1] and scale-free property [2], complex networks have attracted growing interest [3]. The power law distribution of node degree and very small distance between nodes can have profound effects on many dynamical processes taking place on networks, including epidemic [4], synchronization [5] and traffic flow [6]. Among the dynamic processes occurring on networks, ensuring free traffic flow is of great significance and research interest. Actually, traffic flow is related to many other processes. Therefore, a great number of works have been carried out for traffic dynamics on regular and random networks. Recently, the traffic flow on scale-free networks has drawn more and more attention [6], [7], [8], [9].

Since the analysis on network traffic efficiency is still missing, we propose a model based on complex network theory, which is shown in Section 2. Then we show some results of applying this model to four cases: i) effects of node capacity; ii) effects of link bandwidth; iii) effects of closing edges; iv) application to urban traffic problem. The simulation results are shown in Section 3. And in Section 4, the paper is concluded.

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II. SIMULATION MODEL

The model starts with generating the underlying network structure. For the scale-free network, we adopt the most general Barabási-Albert (BA) scale-free network model [10]. This model contains the "growth" and "preferential attachment" mechanisms to mimic the development of complex networks: starting from m_0 fully connected nodes, one node with m links is added to the system at each 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., $\Pi_i = \frac{k_i}{\sum_j k_j}$, where j runs over all existing nodes. The BA model have been proved to well present many technical and social networks. In this paper, we set the network size as $N = 1000$.

The capacity of each node is restricted by two parameters: (1) L: its maximum packet queue length; (2) C: the maximum number of packets it can deliver per time step. The capacity of links is restricted by the link bandwidth: B. In each simulation step, the system evolves in parallel according to the following rules:

1. Add Packets - Packets are inserted to the system with a given rate R (packets per time step) at randomly selected nodes and each packet is given a random destination.

2. Navigate Packets - Each node performs a local search among its neighbors [7]. If a packet's destination is found in its nearest neighborhood, its direction will be directly set to the target. Otherwise, its direction will be set to a neighboring node h with preferential probability: $P_h = k_h^{\phi}/\Sigma_i k_i^{\phi}$. Here the sum runs over the neighboring nodes; k_i is the degree of node i. This conceptual model can be tuned by the only parameter ϕ: packets are more ready to go to a neighboring hub node when $\phi > 0$, and they are more likely to go to a minor node when $\phi < 0$.

3. Deliver Packets – At each step, all nodes can deliver at most C packets towards its destinations and FIFO (first-in-first-out) queuing discipline is applied. Once a packet arrives at its destination, it will be removed from the system. We treat all nodes as both hosts and routers for generating and delivering packets.

III. OPTIMIZATION RESULTS

To characterize the phase transition from free flow to congestion, we introduce an ordering parameter to the evolution of packet number $N_p(t)$ in the system:

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

where ${}^{\Delta} N_p = N_p(t +^{\Delta} t) - N_p(t)$ with $\langle ... \rangle$ takes average over time windows of width ${}^{\Delta} t$. Obviously, $\eta(R) = 0$

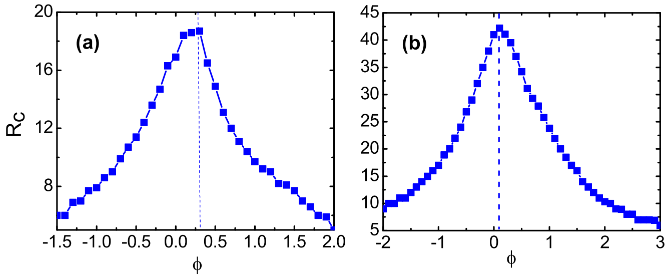

Fig. 1. The overall capacity of a BA scale-free network with size 1000. (a) $\alpha = 1$, $\beta = 0.2$, and $\phi_c = 0.3$ with $R_c^{max} = 18.7$. (b) $\alpha = 2$, $\beta = 0.2$, and $\phi_c = 0.1$ with $R_c^{max} = 42.2$. The unit of R_c is 'packets', and the same is with the following figures.

corresponds to the cases of free flow state, which is attributed to the balance between the number of added and removed packets at the same step. As the inserting rate R increases, there is a critical point of R_c at which N_p increase quickly towards the system's maximum capacity and $\eta(R)$ increases suddenly from zero. This indicates that packets accumulate in the system and thus congestion emerges. Hence, the system's overall capacity can be measured by the critical value of R_c below which the system can maintain its efficient functioning.

A. *Effects of node capacity*

When applying this model to the packet flow in an information traffic system, we set the model to be: $L_i = \alpha \times k_i$, $C_i = \beta \times L_i$, and $B = \infty$. L_i and C_i is set to be proportional to the degree of the router, representing that the hub nodes have more capacity than the minor nodes. The node capacity can be tuned by the parameters α and β.

In Fig.1, the results of two different α values with the same $\beta = 0.2$ are shown. One can see that there is an optimal strategy of routing parameter for the system. When $\alpha = 1.0$, the optimal routing strategy is $\phi_c = 0.3$ with $R_c^{max} \approx 19$. This means to suggest packets to slightly take advantage of hub nodes in their forwarding. When $\alpha = 2.0$, the system's overall capacity is greatly improved with $R_c^{max} \approx 45$, which is more than doubled than the previous case. However, the optimal routing strategy changes to $\phi_c = 0.1$, which is closer to a random walk.

The results are different from previous studies which do not consider the effects of node capacity [7]. If one sets $L_i = \infty$ and $C_i = constant$, the optimal strategy will be $\phi_c = -1.0$. This means to push packets to use minor nodes first. If one sets $L_i = \infty$ and $C_i = k_i$, the optimal strategy will be $\phi_c = 0.0$, which is exactly the random walk. Our results suggest that it is good to slightly encourage packets to use hub nodes, which is more in consistence with real situations.

B. *Effects of link bandwidth*

The effects of bandwidth can also be easily investigated by our simulation model. Here we focus on the effects of bandwidth B on the system capacity R_c and the optimal routing strategy.

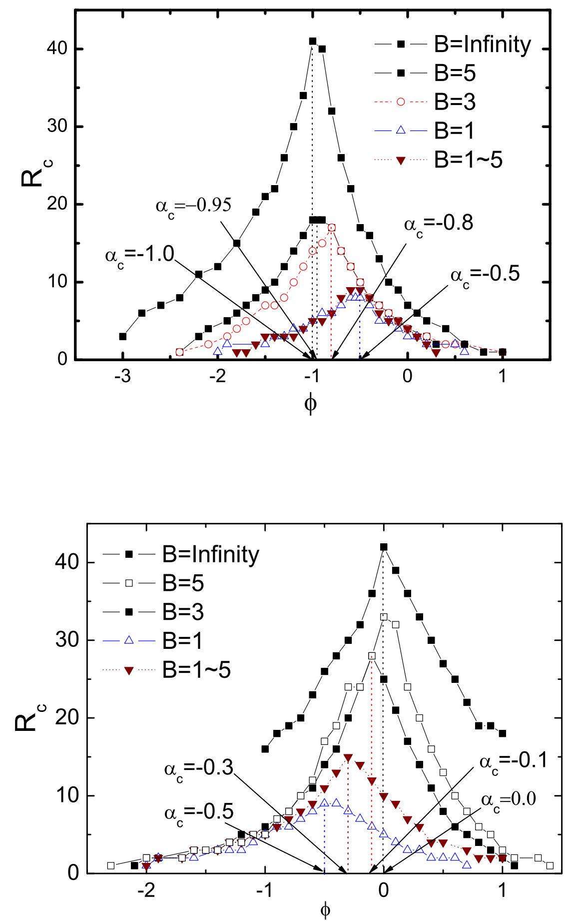

Fig. 2. (Color online.) The network capacity R_c against ϕ with network size $N = 1000$ for different bandwidth B cases. (a) Constant node delivering ability $C = 10$; (b) Heterogeneous node delivering ability $C = k$.

In Fig.2, the simulation results are shown. We consider $L_i = \infty$ with two cases of node delivering capacity: (i) Homogeneous case: $C = 10$ for all nodes; (ii) Heterogeneous case: $C_i = k_i$. For both cases, the system capacity will decrease when the link bandwidth decrease from infinity to a small value. However, the optimal routing strategy show different behavior for the two cases. For the constant node capacity case, the optimal strategy will change from $\phi_c = -1.0$ to $\phi_c = -0.5$. For the heterogeneous node capacity case, the optimal strategy changes from $\phi_c = 0.0$ to $\phi_c = -0.5$. For very low value of bandwidth (B=1), the behaviors of the two system are very similar. That is because the capacity of system is restricted mainly by the link bandwidth effect at this point. Enhancing node capacity, however, can not improve the network capacity when the link bandwidth is very low.

C. *Enhance network capacity by closing edges*

Although many studies focused on developing better routing strategies, it is valuable to develop some strategies by

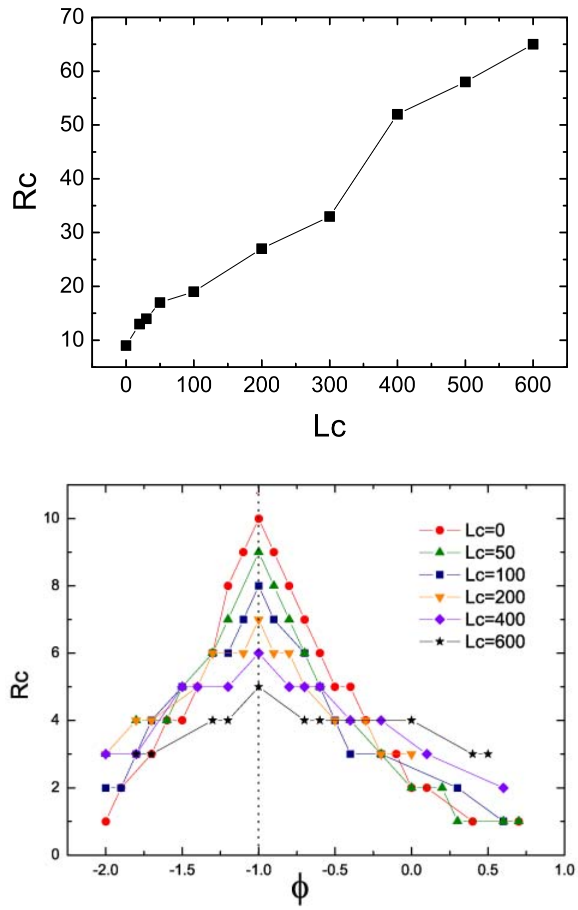

Fig. 3. (Color online.) The network capacity R_c for different number of closed edges L_c. (1) Shortest path routing strategy; (2) Local routing strategy.

modifying the underlying network structure. Here we propose a method by closing some key connections to improve the overall capacity of traffic networks. The method is inspired by that some on-ramps and/or off-ramps are closed at rush hours to alleviate congestion in highway traffic.

We firstly rank links according to the product of each link's end-nodes' degree $\chi = k_m \times k_n$. Then we close the links according to the order of χ value from big to small. Closing these links will redistribute the traffic loads and enhances the network capacity. The closing of links stops when the network is separated into two or more components.

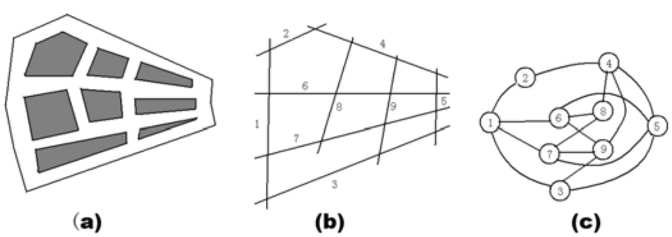

Fig. 4. Basic steps of the dual representation. (a) The original road network; (b) The road segments are grouped based on the line of sight; (c) The dual graph of road network.

Fig.3 shows the network capacity R_c for different number of closed edges L_c. One can see that the network capacity is remarkably enhanced for the shortest path strategy. R_c is enhanced from 10 to about 65 when L_c increase from 0 to 600. But the average travelling time of packets will increase due to the increment of the length of shortest pathes. In the case of local routing strategy, the maximal network capacity R_c^{max} will decrease after closing the key links. The optimal routing strategy keeps at $\phi = -1.0$. However, at the same time, R_c become larger when α deviates from -1.0. Thus the sacrifice in R_c^{max} may be worthwhile when the packets are not forwarded with an uniform strategy or when the system have heterogeneity in routing protocol.

D. Application to the urban traffic

When applying the model to an urban traffic system, we need change the urban topology to a "dual graph" [11], [12], [13]. The basic steps of a dual representation can be illustrated as in Fig.4. Here each straight street is turned into one node, while each intersection is turned into one link between the corresponding pair of nodes. Empirical evidences have shown that the degree distribution of most cities follow a power law [14], [15], [16], [17], [18]

The trajectory of a vehicle can be interpreted as traveling along some roads (nodes) for some distance, and then jumping from a node to another node through a link representing an intersection. Therefore, for the traffic model on a dual graph, the node degree k_i corresponds to the number of intersections along road i; the maximal queue length L_i represents the maximum number of vehicles that the road can hold; C_i is the maximum number of vehicles turning from the road into the neighboring roads per time step. Simulation results have shown that there is similar phase transition behavior in this system, and the transition point R_c can also be used to characterize the overall capacity of the urban system. Moreover, the other results of packet traffic system can be modified to reflect the behavior of an urban traffic system [9].

IV. Summary

In summary, traffic dynamics is simulated by a conceptual model. The restriction of node capacity and link bandwidth can be easily considered in the model. The routing strategy of the packets can be tuned by only one parameter. The network capacity can be examined by the critical inserting rate of packets. In the framework of this model, we investigate the optimization strategy under several situations corresponding to the respective realistic problems: (i) the effect of node capacity; (ii) the effect of link bandwidth; (iii) closing key edges; (iv) urban traffic systems. For the first two cases, simulation results have shown that the system capacity is enhanced at some optimal value of routing parameter. In the third case, the system capacity can be enhanced at the cost of increasing packets' travel time. The model can be further extended to study the urban traffic system by adopting the dual representation of a city's road network.

Our work can be helpful for the design and management of modern communication and transportation systems. The optimization methods mentioned in this paper can also inspire some further works in optimization theory.

In the future work, we will consider more key factors affecting the dynamic characteristics of traffic systems. The emergence and dispersion of traffic congestion will be investigated. Some effective routing strategies will be developed.

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