Efficient routing strategies in scale-free networks with limited bandwidth

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We study the traffic dynamics in complex networks where each link is assigned a limited and identical bandwidth. Although the first-in–first-out (FIFO) queuing rule is widely applied in the routing protocol of information packets, here we argue that if we drop this rule, the overall throughput of the network can be remarkably enhanced. We propose some efficient routing strategies that do not strictly obey the FIFO rule. Compared to the routine shortest-path strategy, throughput for both Barabási-Albert (BA) networks and the Internet can be improved by a factor of more than five. We calculate the theoretical limitation of the throughput. In BA networks, our proposed strategy can achieve 88% of the theoretical optimum, yet for the Internet, it is about 12%, implying that we still have a huge space to further improve the routing strategy for the Internet. Finally, we discuss possibly promising ways to design more efficient routing strategies for the Internet.

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I. INTRODUCTION

Many large-scale traffic networks, such as the Internet, phone networks, and airport networks, are known to be scale-free [1,2]. A crucial problem is how to enhance transportation capacity, to which three techniques are usually applied: designing a better assignment of capacity distribution, optimizing the network structure, and improving the routing strategy [3–6]. Consider the most widely used routing strategy, the shortest-path (SP) strategy, where packets are sent via the path with the fewest intermediate nodes from the source to the destination. In a network with heterogeneous degree distribution, congestion first happens on the hub nodes (which usually have the highest loads and greatest betweennesses [7]) and soon spreads to the whole network. Therefore, assigning higher capacities to the nodes with higher loads sharply enhances the throughput of the whole network [8,9]. Given the capacity of each node as well as the SP routing strategy, network throughput can be largely enhanced by optimizing the network structure via the simulated annealing algorithm [10,11] or by simply removing edges connecting large-degree nodes [12] or edges with high betweennesses [13].

Though effective, enhancing capacity or changing the network structure is usually very costly or not allowed. Because much available capacity is wasted due to a decentralized tradeoff between cost and robustness in many infrastructure systems [14,15], more efforts have been made to improve the routing strategy. Yan *et al.* [16] proposed a highly efficient routing strategy that can automatically detour the hub nodes and improve the network throughput without any increase in computational complexity, which has been further applied to local routing [17,18]. Sreenivasan *et al.* [19] introduced a hub-avoidance protocol that works particularly well when the packet-generation rate is close to the absolute upper bound in scale-free networks. Wang *et al.* [20] and Kujawski *et al.* [21] designed dynamic routing strategies. The traffic awareness protocol (TAP) proposed by Echenique *et al.* [22,23] forms the basis of some variations [24,25], in which a node forwards a packet to a neighboring node with the shortest *effective* distance. It was found that an appropriate awareness parameter gives the best performance [22,23]. In addition, systems with limited queuing length were also considered [26–28].

Previous studies overwhelmingly focused on the capacities and/or limited queuing lengths of nodes, yet paid less attention to the bandwidths of edges, such as the link capacity of information packets in the Internet and the number of available seats in air transportation networks [14,15]. Fekete *et al.* showed that much better performance can be achieved when capacities are proportionally distributed to the expected loads of edges [29]. Hu *et al.* studied the effects of bandwidth on the traffic capacity of scale-free networks [30]. Danila *et al.* [31] proposed an algorithm to minimize the maximum ratio of edge betweenness to bandwidth. All the above-mentioned methods use the first-in–first-out (FIFO) queuing rule. In this paper we show that this rule is not necessary and routing strategies without the FIFO rule can remarkably enhance network throughput and reduce average delivery time. Simulation results on artificially generated scale-free networks as well as the Internet demonstrate the advantages of our proposed strategies.

II. MODEL

In our model, all nodes are treated as both hosts and routers for generating and delivering packets, and each link has the same maximum packet delivery capacity. For simplicity, we set the capacity of each link (i.e., bandwidth) $B = 1$; that is, only one packet can be delivered via a link at each time step. Thus, at each time step a node i with k_i links can deliver at most k_i packets one step toward their destinations. The transport processes is as follows.

(1) At each time step, λN packets are generated with randomly chosen starting points and destinations, where N is the number of nodes. Each newly created packet is placed at the end of the queue of its starting node.

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(2) For each node, according to the routing strategy (the details will be introduced in the next section), packets are checked successively on a first-in basis. Once the link suggested by the routing strategy is free, the packet is delivered to its neighboring node through this link; otherwise, it stays in the queue. Therefore, packets do not strictly follow the FIFO rule, though they are checked on a first-in basis.

(3) When a packet arrives at its destination, it is removed from the system; otherwise it is queued.

Consider the order parameter [32]

$$\eta = \frac{1}{\lambda N} \lim_{t\to\infty} \frac{\langle S(t+\Delta t) - S(t)\rangle}{\Delta t}, \tag{1}$$

where $S(t)$ denotes the total number of packets at time step t. When the system is in the congested phase, $\eta > 0$. The threshold λ_c separates the balance phase, $\eta = 0$ and the congested phase, $\eta > 0$. λ_c is the most significant quantity for transportation networks: The larger, the better.

III. ROUTING STRATEGIES

When simply applying the SP strategy, packets are more likely to pass through links with high betweennesses, which may lead to congestion on these links. Therefore, to enhance the congestion threshold λ_c, a routing strategy should adequately use links with low betweennesses. From this point, we propose the following more efficient routing strategies.

(1) The FIFO queuing discipline is followed strictly: Each node i delivers packets one by one from the foremost to the last (of course, it can deliver at most k_i packets, since $B = 1$), and each packet will choose one among all these unoccupied links along the shortest path to the destination. If several links satisfy this requirement, one of them is randomly selected. Notice that a packet may detour if all unoccupied links point to nodes that are farther to the destination than the current node.

(2) At the beginning of each time step, we set a delay $\tau_{i\ell} = \tau_{\ell i} = 0$ on every link. At variance with the strict FIFO rule, each node i checks packets one by one on a first-in basis, yet may deliver them out of this order. A packet is routed to a neighboring node ℓ toward its destination j with the smallest value of *effective distance*, denoted by

$$d_B(\ell) = h d_{\ell j} + (1-h)\tau_{i\ell}, \tag{2}$$

where $d_{\ell j}$ is the topological distance between nodes ℓ and j, and h is the traffic-awareness parameter. If the link $(i \to \ell)$ is unoccupied (i.e., $\tau_{i\ell} = 0$), the packet is delivered; otherwise, this packet is not delivered in this time step and remains queued in its current position. When this packet is delivered, we set $\tau_{i\ell} \leftarrow \tau_{i\ell} + 1$. In this way, packets in a later position have a chance to be delivered earlier, and are routed according to the approximate waiting time for each candidate link; thus, a link may be chosen that points to a node closer to the destination that is not congested. In contrast, packets that go through central links may be delayed even when they lie in top-queue positions.

(3) It is known that the betweenness centrality of a link $(i \leftrightarrow \ell)$ is strongly correlated with its product degree $k_i k_\ell$ [33]. Accordingly, we assign a weight to every link,

$$w_{i\ell} = (k_i k_\ell)^\theta, \tag{3}$$

where θ is an adjustable parameter. Similar to strategy A, this strategy strictly obeys the FIFO rule but uses the weighted shortest path.

(4) This strategy is a weighted version of strategy B that also does not obey the strict FIFO rule. Equation (2) is replaced by a weighted version per Eq. (3), as

$$d_D(\ell) = h d_{\ell j} + (1-h)\tau_{i\ell} w_{i\ell}. \tag{4}$$

IV. SIMULATION RESULTS

This section compares the different routing strategies in Barabasi-Albert (BA) networks [34], where performance is quantified by the network throughput λ_c. The parameter θ is fixed at $\theta = 0.25$ since at that point the weighted betweenness of a node is approximately linearly correlated with its degree. As shown in Figs. 1(b) and 2, subject to the largest λ_c, the optimal h for strategies B and D is about 0.8 and insensitive to network sizes and degree distributions; thus, in the simulation, $h = 0.8$ is also fixed.

Figure 1(a) depicts the phase transition for different routing strategies, where $\lambda_c = 0.25$ (SP) < 0.55 (A) < 1.00 (B, $h = 0.8$) < 1.05 (C) < 1.30 (D, $h = 0.8$). The SP strategy is worst, because it cannot well use the capacities of small-betweenness links. Under the SP strategy, too many packets jam large-degree nodes and the number of packets queuing at a node is superlinearly correlated with its degree. As shown in Fig. 3, $B(k) \sim n(k) \sim k^\alpha$ with $\alpha \approx 1.6$, where $B(k)$ is the average betweenness over nodes with degree k, and $n(k)$ is the average number of packets over nodes with degree k. This result is in accordance with previous observations [36,37]. Much differently, for the proposed strategies A–D, the small-betweenness links are well used and thus the number of packets waiting at a node is more or less linearly correlated to its degree (see Fig. 3).

Although strategy A makes all links almost fully utilized, massive bandwidths (links) are squandered since many packets

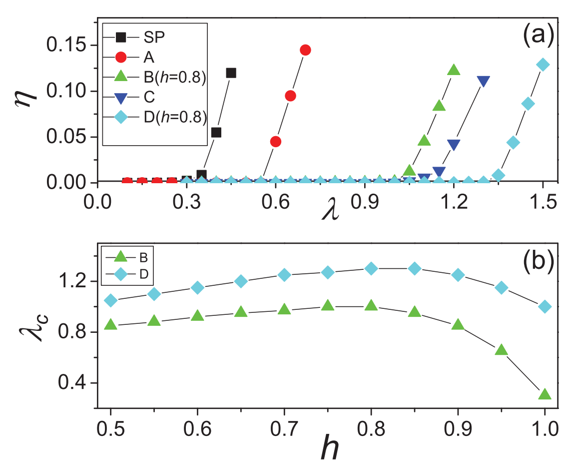

FIG. 1. (Color online) Comparison among different routing strategies in BA networks with $N = 2000$ and $m = m_0 = 3$, where m_0 and m are numbers of starting nodes and new links are added at every time step, respectively. (a) The order parameter η as a function of λ. (b) The network throughput λ_c averaged over 100 independent realizations as a function of the traffic-awareness parameter, where the error bars of the simulation results are less than the symbol size.

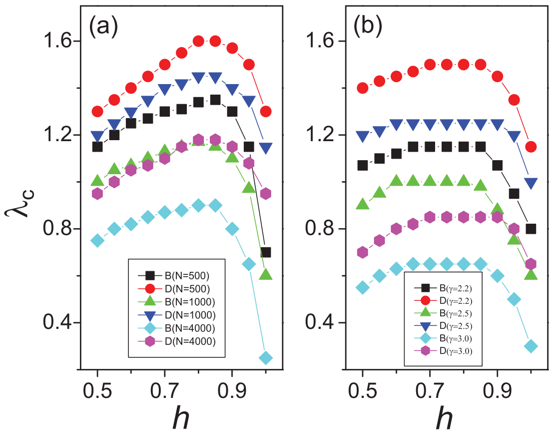

FIG. 2. (Color online) The network throughput λ_c as a function of the traffic-awareness parameter for (a) different network sizes of BA networks and (b) different degree distributions of the uncorrelated configuration models (UCM) [35] with $N = 2000$ and $3 < k < N^{\frac{1}{\gamma-1}}$. The results are obtained by averaging over 100 independent realizations.

detour and pass long paths to the destinations. Taking into account both the shortest path to the destination and the delay of a candidate link, strategy B introduces the effective distance, and thus a vacant path may be selected instead of the shortest path. Compared to the strict FIFO queuing discipline in strategy A, strategy B is more flexible and performs better. As shown in Fig. 3, the slope of the $n(k)$ curve for strategy B ($h = 0.8$) is much less than that for strategy A, indicating that the small-betweenness links are used more effectively.

By equilibrating each link's real traffic load, strategy C can raise λ_c relative to strategy B. However, this strategy is not optimal due to time-dependent fluctuations of the number of packets passing through each link [38–43]. Considering an example with an average of 0.95 delivered packets through a certain link per time step—that is to say, ignoring fluctuations—no congestion happens. However, a huge fluctuation (possibly caused by unequal distribution of starting points and destinations) may line up several packets in this link and thus lead to local congestion, which further depresses the transportation efficiency of the whole network. In other words, strategy C is very good as a static strategy, but fails to capture

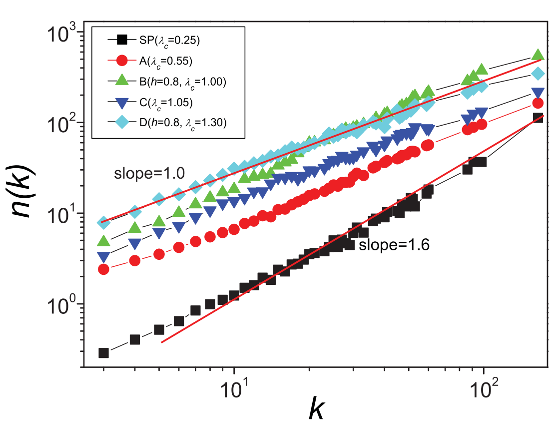

FIG. 3. (Color online) The average number of packets $n(k)$ over the nodes with degree k. Network parameters are the same as in Fig. 1.

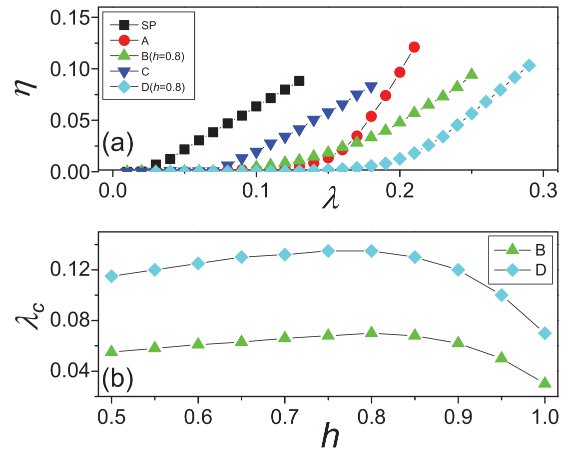

FIG. 4. (Color online) Comparison of different routing strategies for the Internet. (a) The order parameter η as a function of λ. (b) The network throughput λ_c as a function of the traffic-awareness parameter.

real-time traffic in the network. For this reason, delivering queued packets to vacant paths may lead to a considerable improvement of the throughput. Compared with the unweighted effective distance in strategy B, introducing weighted effective distance (see strategy D) increases λ_c to 1.30.

In the ideal condition where $\sum_i k_i$ packets are delivered and each takes the shortest path to the destination without any delay, the theoretically largest throughput λ_u obeys the equality

$$\lambda_u N = \frac{\sum_i k_i}{\langle L \rangle}, \tag{5}$$

where the left side represents the packets generated in one time step and the right side is the maximally possible number of packets that can be delivered to the destination in one time step ($\sum_i k_i$ is the maximal delivering capacity for $B = 1$, and $\langle L \rangle$ is the shortest average time of deliveries per packet). Therefore,

$$\lambda_u = \frac{\sum_i k_i}{\langle L \rangle N} = \frac{\langle k \rangle}{\langle L \rangle}. \tag{6}$$

In BA networks with $N = 2000$, $\langle k \rangle = 6$, and $\langle L \rangle \approx \langle d \rangle = 4.0589$, $\lambda_u = 6/4.0589 \approx 1.48$. Of course, owing to the complicated local structure of networks and real-time fluctuations, the theoretical limitation λ_u cannot be achieved. However, the throughput of strategy D ($\lambda_c = 1.30$) is about 88% of the theoretical limitation.

V. INTERNET RESULTS

In this section, we apply the proposed strategies on the Internet at the autonomous system (AS) level,[1] where the network size $N = 6474$, the average degree $\langle k \rangle \approx 3.88$, the average distance $\langle d \rangle \approx 3.71$, the maximum degree $k_{\max} = 1458$ and the power-law exponent of the degree distribution $\gamma = 2.2 \pm 0.1$. As shown in Fig. 4(a), the proposed routing

[1]The National Laboratory for Applied Network Research, sponsored by the National Science Foundation, provides Internet routing related information based on border gateway protocol data (see http://snap.stanford.edu/data/.)

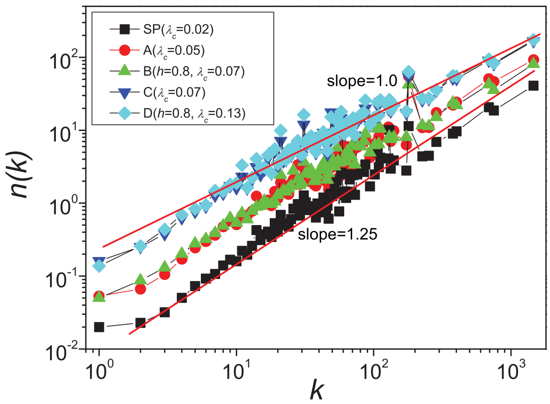

FIG. 5. (Color online) The average number of packets $n(k)$ over the nodes with degree k for the Internet.

strategies are more efficient than the simple SP strategy or the strict FIFO rule of strategy A: $\lambda_c = 0.02$ (SP) < 0.05(A) < 0.07 (B, $h = 0.8$) $= 0.07$ (C) < 0.13 (D, $h = 0.8$). Similar to observations for BA networks, strategy D ($h = 0.8$) also performs best, with the corresponding $n(k)$ curve having a slope of about 1 (see Fig. 5). From Fig. 4(b), we see that the optimal h for strategies B and D is about 0.8, as it is with BA networks, indicating that this optimal value may not be very sensitive to the network structure.

Owing to the structural properties of the Internet, such as disassortative mixing, clustering coefficient, and community structure [44–48], as shown in Fig. 5, there is much greater fluctuation of the mean packet number $n(k)$ compared to BA networks. It implies that some links and nodes are overloaded while some others are largely wasted. As a result, the throughput of strategy D($\lambda_c = 0.13$) is only about 12% of the theoretical limitation ($\lambda_u = 3.88/3.71 \approx 1.04$), which is much less than 88% in BA scale-free networks. This result to some extent explains why it is necessary to install interchangeable paths or increase bandwidths of those links with high betweennesses in order to enhance the total capacity of the Internet [49], and it leaves a huge space for us to further improve throughput by designing a smart routing strategy properly taking into account the structural features of the Internet.

VI. CONCLUSION AND DISCUSSION

We have studied traffic dynamics with limited link bandwidth. Although the first-in–first-out (FIFO) queuing rule is applied everywhere, we argue that if we drop this rule, the overall throughput of the network can be enhanced. Comparing strategy D with the shortest-path strategy (SP) and strategy A's strict FIFO rule, throughput is enhanced by more than a factor of five in BA networks. We have also applied this strategy to the Internet, and, compared with the SP strategy and strategy A, throughput is improved, respectively, by factors of 6.5 and 2.6. Another probable advantage (not yet fully demonstrated) is that the optimal value of key parameter h seems insensitive to the network structure, as for both BA networks and the Internet the optimal values is about 0.8.

In BA networks, the performance of strategy D is close to the theoretical limit (i.e., 88% of the theoretical optimum). However, for the Internet, this fraction becomes much lower, about 12%. This indicates that the structural properties of BA networks are far different from those of the Internet, and the complicated local structure of the Internet, with such features as mixing patterns, clustering, cliques, loop structure, and community structure, makes the design of an advanced routing strategy much harder. Further improvement can be achieved by real-time routing strategies (though these require great computational power and other advanced techniques) or a smarter routing strategy that takes into consideration the structural features of the Internet. Possibly, we should follow the suggestions by Zhao *et al.* [8] and Serrano *et al.* [49] that the bandwidth of each link be carefully assigned in a heterogeneous way.

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