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 proposed some efficient routing strategies that do not strictly obey the FIFO rule. Comparing with the routine shortest path strategy, the throughput for both Barabási-Albert (BA) networks and the real Internet, the throughput can be improved more than five times. We calculate the theoretical limitation of the throughput. In BA networks, our proposed strategy can achieve 88% of the theoretical optimum, yet for the real Internet, it is about 12%, implying that we have a huge space to further improve the routing strategy for the real 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 call networks and airport networks, are known to be scale-free [1, 2]. A crucial problem is how to enhance the transportation capacity, where three kinds of techniques are usually applied: to design a better assignment of capacity distribution, to optimize network structure, and to improve the routing strategy [3, 4]. Considering the most widely used routing strategy, the so-called shortest path (SP) strategy, where packets are sent via the path with the minimum number of intermediate nodes from the source to the destination. In a network with heterogeneous degree distribution, the congestion firstly happens on the hub nodes (they are usually of the highest loads/betweennesses [7]) and soon spreads to the whole network. Therefore, assigning higher capacities to the nodes with higher loads will sharply enhance the throughput of the whole network [8, 9]. Given the capacity of each node as well as the SP routing strategy, the network throughput can be largely enhanced by optimizing the network structure by using the simulated annealing algorithm [10, 11], or by simply removing edges connecting large-degree nodes [12] or with high edge betweennesses [13].

In spite of the effectiveness, to enhance the capacity or to change the network structure is usually very costly or not allowed, and thus more efforts have been paid on improving the routing strategy. Yan et al. [14] proposed a highly efficient routing strategy that can automatically detour the hub nodes, which can remarkably improve the network throughput without any increasing of computational complexity and can be further applied in local routing [15]. Sreenivasan et al. introduced a hub avoidance protocol that works particularly well when the packet-generating rate is close to the limitation [16]. Wang et al. [17] and Kujawski et al. [18] designed the dynamical routing strategies. Systems with limited queuing length were also considered [19–23].

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 the air transportation networks. Fekete et al. showed that much better performance can be achieved when capacities are distributed proportional to the expected load of edges [26]. Hu et al. studied the effects of bandwidth on the traffic capacity of scale-free networks [27]. Danila et al. [28] proposed an algorithm to minimize the maximum ratio of edge betweenness to bandwidth. All the above-mentioned methods embed the first-in-first-out (FIFO) queuing rule, in contrast, we show in this paper that the FIFO rule is not necessary and routing strategies without FIFO rule can remarkably enhance the network throughput and reduce the average delivering time. Simulation results on artificially generated scale-free networks as well as real Internet demonstrate the advantages of our proposed strategy.

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 capacity of delivering packets. For simplicity, we set the capacity of each link (i.e., bandwidth) $B = 1$, namely 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, $\lambda N$ 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.

(2) For each node, according to the routing strategy (the de-
If there are several links satisfying the requirement, one of them will choose the link along the shortest path to the destination. B to the last (of course, it can deliver at most one packet since \( B = 1 \)), and among all the unoccupied links, each packet will choose the link along the shortest path to the destination. If there are several links satisfying the requirement, one of them is randomly selected. Notice that, a packet may detour if all the unoccupied links point to nodes who is further to the destination than the current node.

B. At the beginning of each time step, we set a time delay \( \tau_{id} = \tau_{ji} = 0 \) on every link. Different from the strict FIFO rule, each node \( i \) checks packets one by one following FIFO rule yet may not deliver them in such order. A packet will choose a neighboring node \( \ell \) towards its destination \( j \) with the smallest value of effective distance denoted by

\[
d_B(\ell) = h d_{\ell j} + (1 - h) \tau_{\ell j},
\]

where \( d_{\ell j} \) is the topological distance between nodes \( \ell \) and \( j \), and \( h \) is the traffic-awareness parameter. If the link \( (i \rightarrow \ell) \) is unoccupied (i.e., \( \tau_{\ell i} = 0 \)), the packet will be delivered, otherwise this packet will not be delivered in this time step but still queued up in its current position. Whatever this packet has been delivered, we set \( \tau_{\ell i} \leftarrow \tau_{\ell i} + 1 \). In this way, packets in the later position have the chance to be delivered at an earlier time, and they are aware of the approximated waiting time of each candidate link and thus may choose a link who points further node to the destination but is not congested. In contrast, packets willing to go through central links may be delayed even they lie in top positions of the queue.

C. It is known that the betweenness centrality of a link \( (i \leftrightarrow \ell) \) is strongly correlated with its product degree \( k_i k_\ell \) \[30\]. Accordingly, we assign a weight to every link as

\[
w_{i\ell} = (k_i k_\ell)^\theta,
\]

where \( \theta \) is an adjustable parameter. Similar to the strategy A, this strategy strictly obeys the FIFO rule but it uses weighted shortest path.

D. This strategy is a weighted version of the strategy B, also does not obey the strict FIFO rule. The Eq. \ref{eq:2} is replaced by a weighted version according to Eq. \ref{eq:3}, as

\[
d_D(\ell) = h d_{\ell j} + (1 - h) \tau_{\ell j} w_{i\ell}.
\]

III. ROUTING STRATEGIES

When simply applying the SP strategy, packets are more likely to pass through the links with high betweenness, which may lead to congestion on these links. Therefore, to enhance the congestion threshold \( \lambda_c \), a routing strategy should adequately utilize the links with low betweenness. From this point, we propose some more efficient routing strategies as follows.

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

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In BA networks with (time fluctuations, actually, the theoretical limitation to the complicated local structure of networks and the real-time distance is introduced into the strategy D (in the same way to passing through each link [34, 35]. That is to say, the strategy to the time-dependant fluctuation of the number of packets or less the same, which has a slightly higher threshold than more effectively.

the largest correlated with its degree. As shown in Fig. 1(b), subject to the weighted betweenness of a node is approximately linearly curve for strategy B (n
\[ \lambda \approx \langle k \rangle \approx k^\alpha \] 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 [32, 33]. Much differently, for the proposed strategies (A-D), the small-betweenness links are well utilized and thus the number of packets waiting at a node is more or less linearly correlated with its degree (see also Fig. 2).

Although strategy A makes all links almost fully utilized, massive bandwidths (links) are squandered since many packets will detour and pass long paths to the destinations. Taking into account both the shortest path to the destination and the time 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 with the strict FIFO queuing discipline in strategy A, the strategy B is more flexible and performs better. As shown in Fig. 2 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 utilized more effectively.

Strategy C makes the real traffic load of each link more or less the same, which has a slightly higher threshold than that of the strategy B. However, this strategy isn’t optimal due to the time-dependant fluctuation of the number of packets passing through each link [34, 35]. That is to say, the strategy C is very good as a static strategy while it fails to capture the real-time traffic in the network. Once the effective weighted distance is introduced into the strategy D (in the same way to what we did for the strategy B), \( \lambda_c \) will increase to 1.30.

In the ideal condition where \( \sum_i k_i \) packets are delivered and each of them takes the shortest path to the destination without any delay. The theoretically largest throughput reads

\[ \lambda_u = \frac{\sum_i k_i}{\langle L \rangle N} = \frac{\langle k \rangle}{\langle L \rangle}. \]  

In BA networks with \( N = 2000 \), \( \langle k \rangle = 6 \) and \( \langle L \rangle \approx \langle d \rangle = 4.0589 \), we have \( \lambda_u = 6/4.0589 \approx 1.48 \). Of course, owing to the complicated local structure of networks and the real-time fluctuations, actually, the theoretical limitation \( \lambda_u \) can’t be achieved. Not so bad, the throughput of the strategy D (\( \lambda_c = 1.30 \)) is about 88% of the theoretical limitation.

IV. SIMULATION RESULTS

This section compares different routing strategies in Barabasi-Albert (BA) networks [31], where the performance is quantified by the network throughput \( \lambda_c \); the larger the better. The parameter \( \theta \) is fixed as \( \theta = 0.25 \) since at that point the weighted betweenness of a node is approximately linearly correlated with its degree. As shown in Fig. 1(b), subject to the largest \( \lambda_c \), the optimal \( h \) for both strategies B and D is about 0.8, and thus in the simulation, \( h = 0.8 \) is also fixed.

Fig. 1(a) reports 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 the worst one since it cannot well utilize the capacities of small-betweenness links. Under the SP strategy, too many packets jam at the large-degree nodes and the number of packets queuing up at a node is superlinearly correlated with its degree. As shown in Fig. 2, \( B(k) \sim n(k) \sim k^\alpha \) 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 [32, 33]. Much differently, for the proposed strategies (A-D), the small-betweenness links are well utilized and thus the number of packets waiting at a node is more or less linearly correlated with its degree (see also Fig. 2).

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V. ANALYZING REAL INTERNET

In this section, we will apply the proposed strategies on the real Internet at autonomous system (AS) level [30], 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 \( k_{max} = 14585 \) and the power-law exponent of the degree distribution \( \gamma = 2.2 \pm 0.1 \). As shown in Fig. 3(a), the proposed routing strategies are more efficient than the simples SP strategy or the strict FIFO rule of the 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 the observations for BA networks, the strategy D (\( h = 0.8 \)) also performs the best, with the corresponding \( n(k) \) curve being of slope about 1 (see Fig. 4). From Fig. 3(b), we are happy to see that the optimal \( h \) for the strategies B and D is about 0.8, same to the case for BA networks, indicating that this optimal value may be not very sensitive to the network structure.

FIG. 3: (color online). Comparison among different routing strategies for the real Internet. (a) The order parameter \( \eta \) as a function of \( \lambda \). (b) The network throughput \( \lambda_c \) as a function of the traffic-awareness parameter.

FIG. 4: (color online). The average number of packets \( n(k) \) over the nodes with degree \( k \) for the real Internet.
Owing to the structural properties of the real Internet, such as disassortative mixing, clustering coefficient and community structure [37-41], as shown in Fig. 4, there is much greater fluctuation of mean packet number $n(k)$ compared with the case of BA networks. It implies that some links and nodes are overload while some others may be largely wasted. As a result, the throughput of the strategy D ($\lambda_c = 0.13$) is only about 12% of the theoretical limitation ($\lambda_c = 3.88/3.71 \approx 1.04$), 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 link-betweenness in order to enhance the total capacity of the Internet [42], and it leaves a huge space for us to further improve the throughput via designing a smart routing strategy properly taking into account the structural features of the real Internet.

VI. CONCLUSION AND DISCUSSION

In conclusion, we have studied the traffic dynamics with limited link bandwidth. Although the first-in-first-out (FIFO) queuing rule is applied everywhere, here we argue that if we drop this rule, the overall throughput of the network can be remarkably enhanced. Taking the strategy D as an example, compared with the shortest path strategy (SP) and the strategy A with strict FIFO rule, the throughput is enhanced to more than five times and more then two times in BA networks. We have also applied this strategy to the real Internet, and compared with the SP strategy and the strategy A, the improvements are 6.5 times and 2.6 times. Another probable advantage (not yet fully demonstrated) is that the optimal value of the key parameter $h$ seems not very sensitive to the network structure, as for the BA networks and the real Internet, the optimal values are both about 0.8.

In BA networks, the performance of the strategy D is close to the theoretical limitation (i.e., 88% of the theoretical optimum). However, for the real Internet, this fraction becomes much lower, about 12%. It indicates that the structural properties of BA networks are far different from the real Internet, and the complicated local structure of the Internet, such as mixing patterns, clustering, cliques, loop structure and community structure, makes the design of an advanced routing strategy much harder. The further improvement can be achieved by (i) real-time routing strategies yet they ask for great computational power and other advanced techniques; (ii) more smart routing strategy taking into consideration the structural features of the Internet. Or, maybe we should follow the suggestions by Zhao et al. [8] and Serrano et al. [42] that the bandwidth of each link should be carefully assigned in a heterogeneous way.

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