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Hybrid routing on scale-free networks

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HIGHLIGHTS

- We propose a novel routing algorithm on scale-free networks called hybrid routing.
- The algorithm incorporates both static and dynamic information.
- Simulations show that it can optimize traffic performance more effectively.
- A count-intuitive and beneficial phenomenon about the traveling time emerges.

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ABSTRACT

We propose a novel routing algorithm to optimize traffic performance on complex networks. It combines static structural properties and dynamic traffic conditions together and therefore can balance the traffic between hubs and peripheral nodes more effectively. Simulation results show that the network capacity can be enhanced considerably, and the average traveling time is also shortened sharply, compared with the other two recently-proposed routing algorithms. The effect of the timescale over which the routing information is updated is also investigated. Moreover, a counter-intuitive and beneficial phenomenon about the average traveling time emerges when the packet generation rate is relatively high.

1. Introduction

Large networked infrastructures, such as power grids, telephone networks, the Internet and transportation networks, have come to pervade many aspects of our lives. Therefore, it is of theoretical and practical significance to investigate the structure and dynamics of such complex networks [1,2]. Since the discovery of the small-world phenomenon by Watts and Strogatz [3] and scale-free networks by Barabási and Albert [4] sheds light on the structural properties of complex networks and makes it more feasible to mimic real-world networks, dynamic properties including network traffic have become a hot and intriguing research topic in different areas.

In the case of network traffic, the main aim is to achieve higher traffic efficiency, including improving the transport capacity and/or shortening the traveling time [5–19]. However, in a real-world traffic network, the traffic efficiency is limited due to the onset of traffic congestion. Therefore, the study on traffic congestion has received much attention in recent years [20–30]. Particularly, it has been widely revealed that both the network topology itself and the routing algorithm used in the network have great impact on the traffic congestion [23,26,29,27,31,30]. To this end, two general types of strategies called "hard" and "soft" strategies have been proposed to control the congestion and improve the traffic efficiency [31].

Removing or adding nodes or links in networks has been investigated to optimize the traffic efficiency [5–8]. This kind of methods are called "hard" strategies since they change the physical network infrastructure. On the other hand, the "soft" strategies do not influence the infrastructure. Instead, they try to find better paths for the traffic, i.e., to design better routing

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strategies. Compared with the high cost of "hard" strategies, their "soft" counterparts seem to be more practical to improve the traffic efficiency.

The most straightforward routing strategy is the shortest path routing. However, this routing algorithm usually causes the collapse of hub nodes (i.e., high-degree nodes) due to their heavy load. To design better routing strategies, two kinds of information has been used [9,11–15,19]. First, it is shown that network structure plays a very important role in controlling traffic performance [26,23]. For a fixed network, the structural properties usually do not change. Thus, we call them static information. The most used static information is the node degree. Yan et al. proposed a strategy in Ref. [15] called efficient routing, in which a packet chooses a path with the lowest aggregate degree from the source to the destination. In this way, the packet tends to bypass hubs. The traffic capacity can be enhanced significantly compared with the shortest path routing. Similarly to Yan's strategy, the efficient routing based on local information was also proposed [9]. The above two strategies emphasize the key role of peripheral nodes (i.e., low-degree nodes). On the other hand, the second kind of information shows the dynamic traffic conditions such as the waiting time and the queue length at each node. Based on this kind of information, traffic-awareness strategy [12,13], adaptive routing strategy [11], global dynamic routing [19] and the optimal local routing strategy [14] were proposed.

Previous results indicate that both the static structural properties and dynamic traffic conditions can affect the routing efficiency, and accordingly both aspects should be considered in order to design better routing algorithms. Surprisingly, very little literature considers both aspects at the same time. In Ref. [10], a routing strategy based on the local static and dynamic information was proposed. In this strategy, the probability that a packet at the node l goes to its neighboring node i is given by

$$P_{l\to i} = \frac{k_i(q_i+1)^\beta}{\sum\limits_j k_j(q_j+1)^\beta}, \tag{1}$$

where q_i is the queue length at node i, and the denominator runs over all neighbors of node l. However, instead of providing a mechanism to govern the balance of the traffic among different nodes effectively, the integration intends to encourage packets to pass through hub nodes.

Motivated by above facts, we propose an efficient global routing algorithm by incorporating the node degree distribution, the waiting time and queue length at different nodes in networks. Since different kinds of information is considered, we call it as *hybrid routing*. Our aim is to balance the traffic of networks more effectively and further optimize the traffic performance.

2. Network structure and traffic model

Empirical studies reveal that the degree distributions of many traffic networks obey the power-law distribution $P(k) \sim k^{-\gamma}$, where k is the node degree and $\gamma > 0$ is the algebraic scaling exponent [4,32]. In this paper, the well-known BA scale-free network model [4] is adopted to mimic the underlying network. Starting with m_0 fully connected nodes, at every time step we add a new node with m ($\leq m_0$) edges linked to m different nodes based on a preferential attachment rule, i.e., the probability of being connected to existing node i is proportional to its degree k_i. Finally, the resulting network is a scale-free network with a degree distribution $P(k) \sim k^{-3}$.

In such a network, packets are generated at their sources and are delivered to their destinations. The main reason for traffic congestion during the delivery comes from the limited processing capacity of nodes. In real-world situations, hubs usually need to handle more traffic load than other nodes, and therefore they are usually assigned larger processing capacities. To capture this fact, the processing capacity is often assumed to be $1+\beta k_i$ for a node with degree k_i [33,34], where $\beta \geq 0$ is an adjustable parameter. Without loss of generality, in this paper we set $\beta = 1$. Then the processing capacity of node i (denoted as c_i) becomes

$$c_i = 1 + k_i. \tag{2}$$

Due to the limited processing capacity, a queue of buffers is needed at each node to save packets waiting for being processed. We assume that the maximal queue length of each node is unlimited and FIFO (first-in-first-out) discipline is adopted while handling the queue.

Our traffic model includes the following two parts.

- Packet processing. At each time step, if it has more than c_i packets waiting in its queue at node i, the first c_i packets are processed. Otherwise, all packets in the queue are processed. For each of these packets, if node i is not its destination, then it is delivered to the next stop towards its destination based on a specific routing algorithm. Otherwise, it is removed from the network.
- Packet generation. At each time step, the network creates R new packets with randomly chosen sources and destinations. For each packet, once its source and destination are fixed, a path from the source to the destination is calculated based on the specific routing algorithm. Then, it is put at the end of the queue at its source node.

We propose a packet routing algorithm called hybrid routing. As we mentioned before, both the network static structural properties (such as the degree distribution) and dynamic conditions (such as the queue length and waiting time for an incoming packet) can affect routing efficiency. Therefore, our routing algorithm takes both aspects into consideration.

Moreover, we try to combine them together more efficiently. Considering the heterogeneous structure, we introduce a dynamic parameter $\alpha(t)$ to measure the dynamic traffic conditions of relatively high-degree nodes. It is the ratio between the sum queue length of nodes with a degree higher than a tunable parameter K_c and the total queue length of all nodes. Thus, it can be denoted as

$$\alpha(t) = \frac{\sum_{i:k_i > K_c} q_i(t)}{\sum_j q_j(t)}, \tag{3}$$

where $q_i(t)$ represents the queue length at node i at time t. The parameter K_c is the cutoff point which distinguishes high-degree nodes from others. It lies in the range $k_{min} \leq K_c < k_{max}$, in which k_{min} and k_{max} are the minimum and maximum of the degree k, respectively. Because the queue length changes from time to time, $\alpha(t)$ is a function of time, which lies strictly in the range $0 < \alpha(t) < 1$. Then we define a weight for node i as

$$w_i(t) = 1 + \frac{q_i(t)}{c_i} + k_i^{\alpha(t)}. \tag{4}$$

The path between node s (source) and node d (destination) can be labeled as $P(s \to d) := s \equiv x_0, x_1, \ldots, x_{n-1}, x_n \equiv d$ [15]. We evaluate the path by its aggregate weight $H_{sd}(t)$:

$$H_{sd}(t) = \sum_{m=1}^{n} w_{x_m}(t). \tag{5}$$

From all paths between nodes s and d, the optimal path can be selected as the one with the minimal $H_{sd}(t)$. Note that the weight $w_i(t)$ changes with time. Therefore the optimal path may be different at different time, even with the same source–destination pair. In this way, the traffic load can be adjusted based on the real-time traffic conditions.

This routing strategy actually includes the effect of both the static structural property and dynamic traffic information a node can have. In the weighting rule (4), the first half $1 + q_i(t)/c_i$ represents the estimated waiting time an incoming packet has to spend until it can be processed at node i [11,14]. To improve the traffic performance, it is better to choose a path with a shorter waiting time. In the second half $k_i^{\alpha(t)}$, k_i shows the static structural property of node i. In a scale-free network, a node with a higher degree tends to handle more traffic load. To achieve a higher traffic capacity, it is better to choose a path which can bypass those hub nodes to some extent [15]. Moreover, the introduction of $\alpha(t)$ in the second half also takes the network dynamic condition into consideration. This exponent shows how heavy the traffic load is on relatively high-degree nodes. If it is high, then the second half takes more weight, which forces more packets to bypass hubs.

To show the traffic efficiency of our hybrid routing algorithm, we also consider the following two routing algorithms for comparison. They use different ways to calculate the weight $w_i(t)$.

- Efficient routing [15]. This routing strategy calculates the weight by using the node degree

$$w_i(t) = k_i. \tag{6}$$

  In this way, only static structural property is considered.
- Global dynamic routing [19]. This routing strategy uses queue length to calculate the weight

$$w_i(t) = 1 + q_i(t). \tag{7}$$

  It is necessary to state that the technical and economical costs of hybrid routing are almost as same as those of global dynamic routing.

In order to characterize the traffic congestion, we use the order parameter introduced in Ref. [28]

$$\eta(R) = \lim_{t\to\infty} \frac{C}{R} \frac{\langle \Delta L \rangle}{\Delta t}, \tag{8}$$

where $L(t)$ is the total number of packets of the network at time t, $\Delta L = L(t + \Delta t) - L(t)$, $\langle \cdots \rangle$ indicates the average over time windows of width Δt, and C is the average processing capacity over all nodes. Actually, the order parameter indicates the traffic status in the macroscopic level. The traffic tie-up will be observed when the packet generation rate R is sufficiently high. Therefore, there will be a critical value R_c characterizing the phase transition from free-flow to jamming. When $R < R_c$, the number of unremoved packets is a constant, making η zero. However, when $R > R_c$, $\langle \Delta L \rangle$ grows linearly with Δt. So η is a constant larger than zero. Therefore, R_c can be a measure of the network traffic capacity.

3. Simulation results

The network traffic efficiency can be measured by two parameters. The first one is the critical packet generation rate R_c. A larger R_c means that the network can handle more packets without congestion, therefore R_c is also viewed as the network

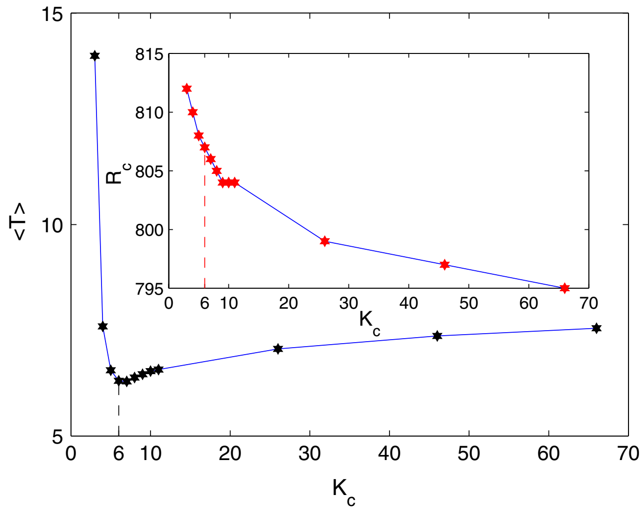

Fig. 1. (Color online) Average traveling time $\langle T\rangle$ versus parameter K_c, with packet generation rate $R = 750$. The inset is the network capacity R_c as a function of parameter K_c. Network size $N = 500$, and average degree $\langle k\rangle = 6$.

capacity. On the other hand, even with the same value of R_c, we want that packets arrive at their destinations as soon as possible. This performance can be measured by the average traveling time of packets $\langle T\rangle$.

As mentioned above, we first investigate the sensitivity of the traffic performance with respect to the cutoff point K_c for hybrid routing. Fig. 1 demonstrates the results in terms of both the network capacity R_c and average traveling time $\langle T\rangle$. We let the network size $N = 500$ and average degree $\langle k\rangle = 6$ in this simulation. As shown in the inset, the network capacity R_c slightly decreases when the cutoff point K_c increases. Specifically, when $K_c = \langle k\rangle = 6$, $R_c = 807$, which is just little less than the maximum $R_c = 812$. The main figure shows the relation between the average traveling time $\langle T\rangle$ and the cutoff point K_c. Here we set the packet generation rate $R = 750$, which, according to the inset, is less than R_c in our simulation with different K_c, corresponding to a free-flow state. One can clearly find that the minimum of $\langle T\rangle$ is achieved with a specific value of K_c close to the average degree $\langle k\rangle = 6$. To this end, it is reasonable to set the cutoff point K_c to be $\langle k\rangle$ since it can achieve high traffic performance in both R_c and $\langle T\rangle$. Moreover, $\langle k\rangle$ is a statistical quantity, which is a determinate value for a specific complex network. Therefore, the average degree $\langle k\rangle$ is selected as the cutoff point K_c in the following simulations.

In Fig. 2(a), we report the simulation results for the relation of the order parameter η versus packet generation rate R for three different routing algorithms with the same network size $N = 500$ and average degree $\langle k\rangle = 6$. As one can see, our hybrid routing algorithm achieves the highest network capacity compared with the other two algorithms. The improvement of network capacity is more than 20% than that of the global dynamic routing algorithm (see Fig. 2(b)). In comparison, the performance of the efficient routing algorithm seems to be the lowest. However, one should notice that this routing algorithm only needs static structural information, whereas the other two routing methods need real-time global dynamic information to facilitate the routing selection. In this sense, the efficient routing algorithm is the simplest.

Fig. 3 shows the network capacity R_c as a function of average degree $\langle k\rangle$ for three routing algorithms with the same network size $N = 500$. It again illustrates that the efficiency of our hybrid routing is the highest compared with the other two routing algorithms.

We also investigate the average traveling time for each routing algorithm when the traffic is in the free-flow state. Fig. 4 gives the simulation results. The average traveling time of the hybrid routing algorithm is significantly less than that of the other two routing algorithms. Taking $R = 650$ for example, the global dynamic routing algorithm achieves a very long average traveling time of $\langle T\rangle \approx 12.5$. It is more than twice of that of the hybrid routing algorithm, which is only about 5. That is to say, compared with the global dynamic routing algorithm, packets can reach their destinations much more quickly by using the hybrid routing algorithm at almost the same technical and economical costs, which is of great importance for modern society.

Above comparisons show that our hybrid routing algorithm outperforms the other two algorithms in both network capacity and average traveling time.

To implement the routing algorithm we have proposed, each node needs to update the routing paths at each time step, which is a time-consuming computation. To make it more practical, we introduce a timescale T_s which gives the frequency the global dynamic information is updated. Our previous simulations give the results with $T_s = 1$. It is obvious that with a larger timescale, a poorer traffic performance is experienced. Fig. 5 shows this effect with more details. We first focus on the sensitivity of the network capacity R_c to the timescale T_s, which is depicted in the inset. When T_s is less than 10, R_c has a slow decline with the increment of T_s. On the other hand, R_c keeps nearly steady for the timescale T_s greater than 10. However, we find that even with a large timescale such as $T_s = 30$, the network capacity R_c of the hybrid routing (=765) is still much larger than that of the global dynamic routing with $T_s = 1$ (=667 as shown in Fig. 2(b)).

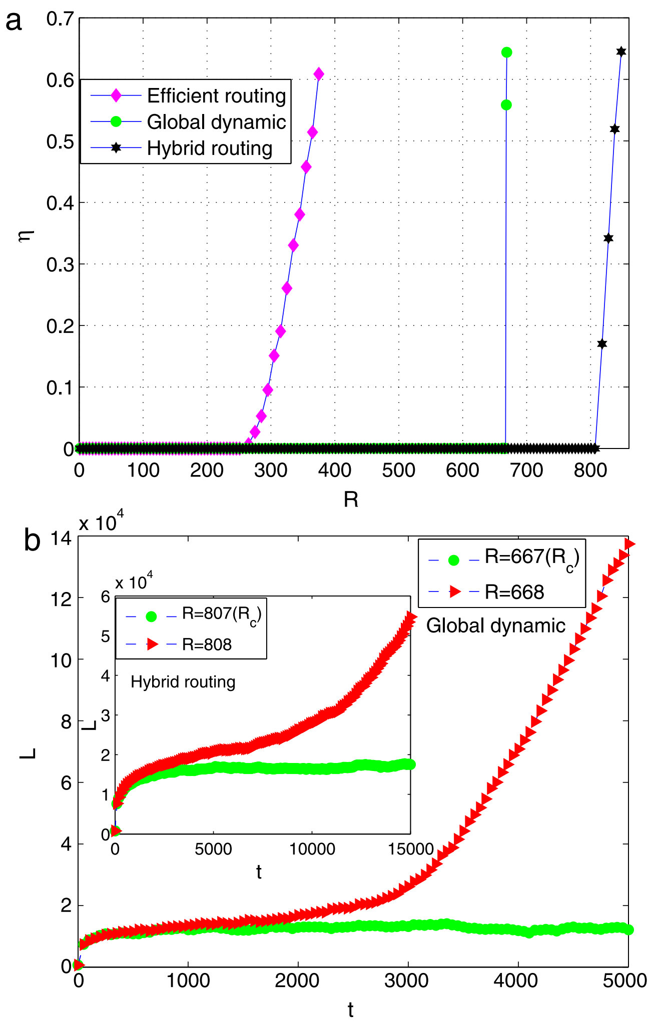

Fig. 2. (Color online) Evolution of total packets for three routing algorithms. (a) Order parameter η versus packet generation rate R for three routing algorithms, (b) the total number of packets L for global dynamic routing and hybrid routing (inset). Network size $N = 500$ and average degree $\langle k \rangle = 6$.

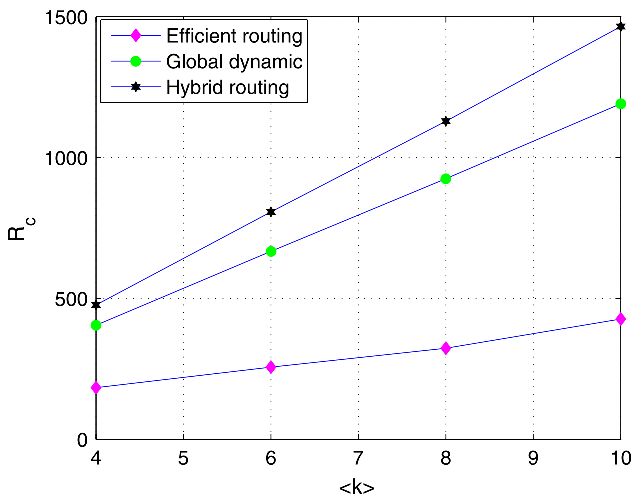

Fig. 3. (Color online) Network capacity R_c versus average degree $\langle k \rangle$ for three routing algorithms with the same network size $N = 500$.

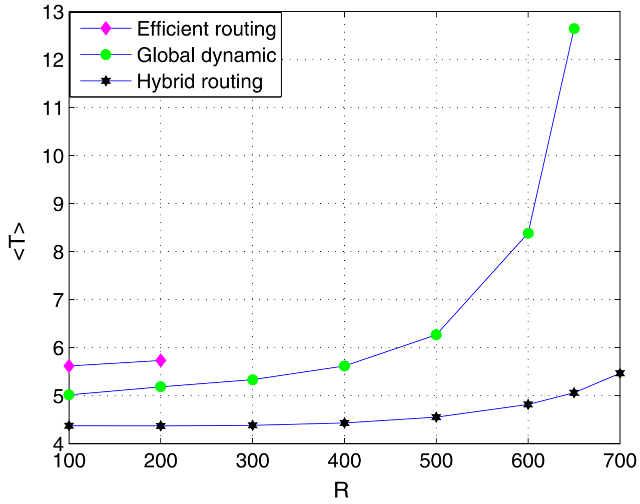

Fig. 4. (Color online) Average traveling time $\langle T\rangle$ versus packet generation rate R for three routing algorithms. Network size $N = 500$ and average degree $\langle k\rangle = 6$.

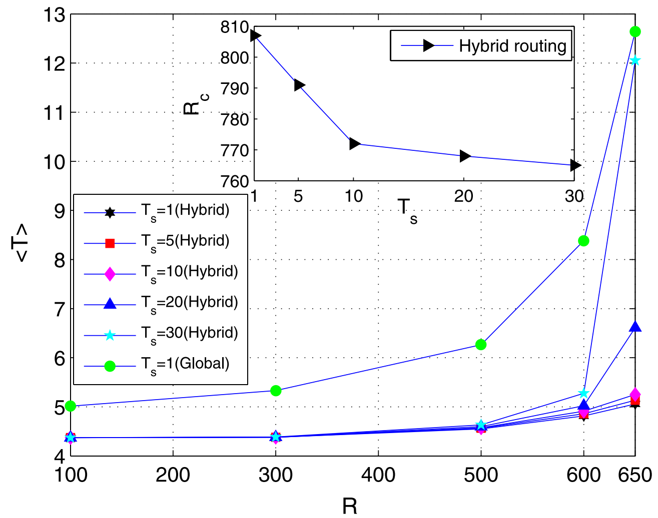

Fig. 5. (Color online) Average traveling time $\langle T\rangle$ versus packet generation rate R with different timescale T_s for hybrid routing and global dynamic routing. The inset depicts the network capacity R_c as a function of timescale T_s for hybrid routing. Network size $N = 500$ and average degree $\langle k\rangle = 6$.

In the main figure of Fig. 5, one can find that the timescale T_s has little impact on the average traveling time $\langle T\rangle$ when the packet generation rate R is relatively low, say, $R \le 600$. However, when R is relatively high, the average traveling time $\langle T\rangle$ increases significantly, particularly for a larger timescale T_s. However, even with a large timescale such as $T_s = 30$, the average traveling time of the hybrid routing is still shorter than that of the global dynamic routing with $T_s = 1$.

Both the main figure and the inset of Fig. 5 indicate that although the timescale T_s degrades the traffic performance, the efficiency of our hybrid routing strategy is still much higher in comparison with the other two routing algorithms.

Next, we make a further study on the average traveling time. As the traveling time for a packet equals to the sum of the time spent at each node on the path from its source to the destination, a natural method is to calculate the waiting time at each node and find a path with the shortest aggregate time. Similar to approaches mentioned above, we can measure the weight by the waiting time

$$w_i(t) = 1 + \frac{q_i(t)}{c_i}, \tag{9}$$

and use Eq. (5) to evaluate the path. Intuitively, packets will experience the shortest estimated traveling time by choosing the path with the smallest aggregate weight (9). We call this method *shortest time routing*.

Fig. 6 represents the simulation results. When the packet generation rate R is relatively low, the shortest time routing algorithm achieves the shortest traveling time. Our hybrid routing algorithm also performs quite well. Its average traveling

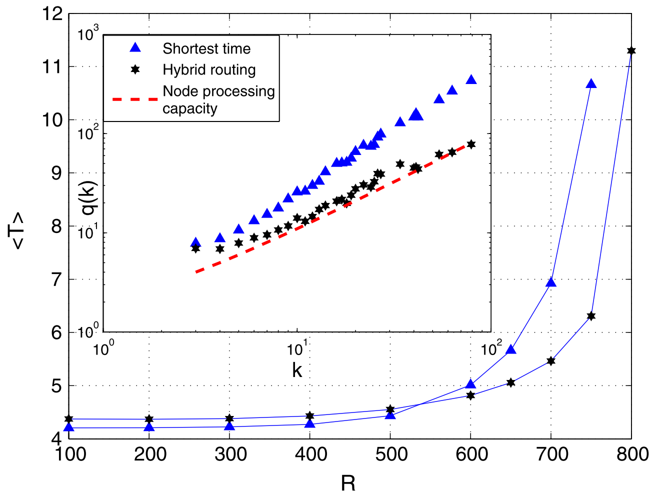

Fig. 6. (Color online) Evolution of average traveling time $\langle T\rangle$ for different R under shortest time routing (blue upward-pointing triangle) and hybrid routing (black hexagram). The inset depicts average queue length $q(k)$ versus node degree k for them, the red dashed line represents the node processing capacity as a function of the node degree k. Network size $N = 500$, average degree $\langle k\rangle = 6$ and packet generation rate $R = 750$ (inset).

time is quite close to that of the shortest time routing algorithm. However, when the packet generation rate R is relatively high, say, greater than 600 in our simulation, there is a counter-intuitive phenomenon that the hybrid routing strategy can achieve a shorter average traveling time than the shortest time routing strategy does. For example, when $R = 750$, the shortest time routing algorithm has to endure an average traveling time as long as about 10.6 time steps, much longer than our hybrid routing costs, which is only about 6.3 time steps. In other words, although the shortest time routing strategy tries to find a path with the shortest estimated traveling time, the resulting path still has to experience a longer time than our hybrid routing strategy can provide.

We believe this counter-intuitive phenomenon comes from the weighting strategies used in different routing algorithms. To explain it, let us first consider the case that the packet generation rate R is relatively low. In our hybrid routing, both the node degree and the dynamic traffic information are used to calculate the node weight. In comparison, the shortest waiting time routing only makes use of the dynamic waiting time. If two nodes have the same waiting time, then our hybrid routing marks the one with a larger degree with a larger weight. In this way, packets prefer to go through low-degree nodes, even if the waiting time is the same, or even a little bit longer. When R is relatively low, this makes our hybrid routing cost a little bit longer traveling time than the shortest time routing experiences. This is why where is always a small time difference between our routing algorithm and the shortest time routing when the packet generation rate R is relatively low.

However, when the packet generation rate is relatively high, the shortest waiting time routing faces a problem. Since it only uses the waiting time to judge nodes, hubs become the most fragile places where packets pile up in the queues, waiting for a long time before being processed. This result is confirmed by Fig. 6(inset), which gives the mean queue lengths, averaged over all nodes with the same degree. It clearly shows that using the shortest time routing, nodes with a larger degree have a longer queue. Then, the newly generated packets have to face a dilemma that either go through hubs, which costs a long time before being processed, or go through peripheral nodes, which costs less waiting time at each node but needs a larger number of hops to reach their destinations. In either way, the total time spent during the transport is long.

In comparison, given the same waiting time, our hybrid routing prefers to use low-degree nodes from the beginning. The dynamic parameter $\alpha(t)$ makes use of queue lengths of different nodes to optimize traffic distribution adaptively. When $\alpha(t)$ increases, $k^{\alpha(t)}$ will take larger weight, which will encourage more packets to bypass high-degree nodes. The above characteristics make the queues at both hubs and peripheral nodes much shorter (also see Fig. 6(inset)). Therefore, the waiting time in queues is dramatically saved. This fact indicates that when the packet generation rate is relatively high, it is better to bypass hub nodes to some extent. We also have checked the shortest time routing in terms of traffic capacity. Simulations indicate that the traffic capacity of the shortest time routing is always smaller than that of the hybrid routing, which further supports the efficiency of the hybrid routing.

4. Conclusions

Different routing strategy uses different method to weigh nodes and accordingly score paths. Usually, two kinds of network properties can be used to measure the node weight. One comes from the static structural properties such as the node degree, and the other is dynamic traffic information such as the real-time queue length or waiting time. For designing a better routing strategy, these two kinds of properties are both important. In this paper, we propose a hybrid routing algorithm for scale-free complex networks. This routing method takes both the static structural property and dynamic traffic information into account. In this way, it can optimize the traffic efficiency. The simulation results indicate that this routing algorithm can enhance the traffic efficiency in terms of the traffic capacity and traveling time. More interestingly, a counter-intuitive phenomenon is found when the packet generation rate is relatively high—our routing algorithm can achieve a shorter average traveling time than the one which aims to minimize it.

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