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Global Hybrid Routing for Scale-Free Networks

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ABSTRACT The performance of routing strategies on complex networks can be characterized by two measurements, i.e., the traffic capacity and the average packets travel time. By efficiently synthesizing the degree and the dynamic queue length of nodes, we propose the global hybrid (GH) routing strategy. It can achieve higher traffic capacity, as well as shorter average packets, travel time compared with the state-of-the-art global dynamic (GD) routing strategy and efficient routing (ER) strategy. Moreover, such superiority can be maintained through the queue length information and the corresponding routing paths are updated periodically. The simulation results show that our GH routing strategy can provide the same traffic capacity as the GD routing strategy does, which is more than twice as high as the ER strategy. At the same time, the average packets travel time of the GH routing strategy is more than 20% smaller than that of the GD routing strategy. It is worth noted that longer updating delay makes our GH routing strategy have a greater decline in the average packets travel time. With the updating delay equals 100, the decline can be up to 40%. To illustrate the practicability of our GH routing strategy, we also applied it to a scale-free network-based data center network. The simulation results reveal that it is practical, effective, and can be used in real scenarios to improve network performance.

INDEX TERMS Scale-free networks, hybrid routing, traffic capacity, average packets travel time.

I. INTRODUCTION

Dynamical properties of complex networks have attracted tremendous attention from researchers. Many real-world networks display both small-world phenomenon and scale-free property [1]–[3], such as the Internet [4], social networks [5]–[7], city transport networks [8]. Other than traditional networks, recent study reveals that cognitive networks and language networks exhibit the scale-free features as well [9], [10]. A scale-free network is a network whose degree distribution follows a power law. The purpose of studying these complex networks is to enhance the traffic capacity and/or shorten the travelling time. Although changing the underlying infrastructure [11]–[17] and developing better routing strategies [12], [13], [18]–[33] can both improve the traffic efficiency. Compared with the former, the latter is preferred for its low cost.

More recently, the booming of fifth generation (5G) mobile communications and the emerging Internet of Things, cloud applications and self-driving vehicle are bringing huge amount of traffic into the networks. For example, according to the statistics, data center traffic grows sharply with 25 percent annually [34]. This overwhelming traffic demands bring heavy burden on network infrastructures. Moreover, increasing infrastructure construction is just a temporary solution, which is quite expensive [35]. So it is of great significance to enhance the traffic capacity to alleviate the dense traffic pressure. What is more, the emergence of Edge computing, augmented reality and some other rising technologies require ultra-low latency. Most of these networks are composed of at least thousands of nodes, which forms scale-free networks as well. Therefore, it is important to introduce better routing strategies to such networks to decrease the end-to-end latency and enhance the traffic capacity.

Traditional shortest path (SP) routing strategy is widely used in real communication networks for its simplicity [18], [19], [30]. However, it often leads to network congestion as large numbers of packets are transmitted through hub nodes with high degree and betweenness [12], [13], [20]–[25]. As a result, it will cause performance degradation to apply SP routing strategy directly to scale-free networks.

There are innumerable routing paths in such a complex network with a large scale. Moreover, different choices for a source-destination node pair usually tend to have distinct

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routing costs and result in markedly different network performance. Hence, it is really a tough job to decide the routing paths for all source-destination node pairs in a network with massive nodes.

Scale-free networks possess some unique characteristics compared with traditional networks. First, they have larger number of nodes, usually more than hundreds of nodes, whose structural attributes follow some statistical characteristics. For example, the scale-free networks are heterogeneous and the degree distributions of the nodes follow the power-law distribution [1]. However, SP routing strategy are more suitable for homogenous networks, such as traditional telecommunication network. So in order to design better routing strategies in scale-free networks, we need to make the best use of their structural properties. In addition, a fine-designed routing strategy should take the dynamic changes of the network into consideration so that the routing can follow the dynamic network environments. For instance, we may adjust the packets to a lighter loaded path to avoid congestion on the burdened links. In this paper, we proposed a routing strategy called global hybrid (GH) routing strategy. It considers both the heterogeneous structural properties and the network dynamics. We test our routing strategy in both synthetic networks and a real data center network. According to the simulation results, our GH outperforms previous methods in terms of traffic capacity and the average packets travel time.

The remainder of this paper is organized as follows. In Section II we introduce the related works in recent years. Section III describes the details of our design, including the routing model and some definitions. Section IV presents the simulation results of the GH routing strategy. Finally, we conclude our work in Section V.

II. RELATED WORKS

Recent years, many alternative routing strategies have been proposed to overcome the obstacles of SP routing strategy under scale-free networks. Wang *et al.* [31] introduced a packet routing strategy based on the local structural information of a scale-free network . Zhang *et al.* [32] proposed a routing strategy to forward the message to a neighbor by estimating the waiting time along the shortest path from each of its neighbors to the destination. Yang *et al.* [33] investigated how to rationally allocate packet-delivering capacity onto nodes in the BA scale-free network when the sum of all nodes' packet-delivering capacity is fixed. These routing strategies based on local information can improve the network performance to a certain extent.

Some other researches mainly focus on designing better routing strategies by taking into consideration the global information of the network. For example, Yan *et al.* [20] developed the efficient routing (ER) strategy , in which a packet tends to bypass the hub nodes (nodes with large degree and many other nodes connected to) and chooses a path with the lowest aggregate degree from the source to the destination. It can achieve a very high traffic capacity, which can be more than ten times that of SP routing strategy. The probability path routing strategy [26] is also dedicated to enhancing the traffic capacity by using the degree information. In the global dynamic (GD) routing strategy [21], the packets are delivered along the path, in which the sum queue length of nodes is a minimum. By considering the dynamic information, the traffic capacity can be further enhanced.

From the work of previous researchers, we can find out that both the static structural properties and the dynamic traffic conditions can affect the routing efficiency. However, only a few routing strategies have integrated both aspects at the same time. In Wang *et al.* [27] proposed a local routing strategy based on the degree and queue length information. Chen *et al.* [22] proposed a traffic awareness routing strategy by integrating the estimated waiting time and shortest path length of neighbor nodes. However, without considering the global information of the network, these two routing strategies forward the packets hop by hop based on the status of the neighbors of a node can only achieve fairly low traffic capacity. In [28], by mixing the dynamic changes of efficient betweenness and degree information of all nodes, the author reported a heuristic routing strategy. Nevertheless, every packet has to go through N (network size) steps to determine a certain path from the source node to the destination node. Therefore, it is too much complicated, time-consuming, and unrealistic to be put into use. Tan and Xia [29] defined weights for all nodes by incorporating the node distribution, the waiting time and queue length at different nodes in networks. It is superior to some former routing strategies. However, the performance will be greatly degraded when the dynamic information is updated with a relatively long period.

To overcome the above shortcomings of previous methods, we propose a routing strategy by integrating the static and dynamic properties at the same time. We search the whole network for an optimal path for every source-destination pair. So we call it a global hybrid (GH) routing strategy. We aim to enhance the traffic capacity and reduce the average packets travel time.

Some previous studies tend to bypass the hub nodes to avoid overburdened traffic transmitted through these nodes. For example, the EP [20] avoid the large degree nodes. However, it is unwise to neglect their positive effect, since through these hub nodes a packet is very likely to find a better path with shorter hops. In a word, we should use the hub nodes in a moderate way. We also hope that our routing strategy is able to follow the dynamic changes of the network environment. Therefore, dynamic queue length information should be taken into account. But there lies a similar question we need to answer: how much should we forward the packets according to the queue length? X. Ling et al. advise to choose a path with totally the lowest queue length from the source to the destination [21]. But this is not always the best choice to make. For instance, the path with lowest aggregate queue length may travel longer route, so its end-to-end latency is not always the smallest. What is more, different nodes make simultaneous decisions for concurrent traffic, so many packets may choose a same node with small queue length at the same which may cause possible congestion.

In our design, we make a linear combination of the degree and queue length for all paths. Furthermore, we determine the most appropriate balance between both aspects. Since we consider the aggregate linear combination, the path length is also taken into account. In the next section, we will discuss the details of our GH routing strategy and some definitions.

III. THE MODEL AND DEFINITIONS

Previous studies reveal that the degree distributions of many communication networks follow the power-law distribution $P(\mathrm{k}) \sim k^{-\gamma}$. The Barabási-Albert (BA) model [1] is most commonly used model, which can generate networks with a power-law degree distribution. For consistency, we construct the network structure using the BA scale-free model. Starting from m_0 fully connected nodes, a new node with m edges ($m \leq m_0$) is added to the existing graph at each time step based on a preferential attachment rule, i.e., the probability $\prod_i$ of being connected to the existing node i is proportional to the degree k_i.

Without loss of generality, we make the following assumptions used in [20], [21], and [26]–[29]:

1. At each time step, there are R packets generated in the system, with randomly selected sources and destinations. Then they are put at the end of the queue at their source nodes.

2. All the nodes are a mix of hosts and routers that can deliver one packet per time step towards their destinations according to the routing table.

3. The queue length of each node is unlimited and the FIFO (first-in-first-out) discipline is applied.

4. Once a packet reaches its destination, it is removed from the network.

To design a more efficient routing strategy, we synthesize the dynamic queue length information and the static degree information in our GH routing strategy. Among all possible paths between the source node s and the destination node d, we choose the one that can be denoted as

$$P_{sd} = \min \sum_{i=0}^{n} \left[\alpha * N_q(i) + (1-\alpha) * N_d(i)\right], \tag{1}$$

where α is a tunable parameter that determines the weight of queue length and degree, and n is the path length. $N_q(i)$ is the normalized queue length of node i, which is defined as

$$N_q(i) = q(i)/\max(q), \tag{2}$$

where $q\,(i)$ is the queue length of node i and $max\,(q)$ is the maximum queue length among all nodes in the network. $N_d(i)$ is the normalized degree of node i, which is defined as

$$N_d(i) = k(i)/\max(k), \tag{3}$$

where $k\,(i)$ is the degree of node i and $max\,(k)$ is the maximum degree of all nodes in the network.

Obliviously, when $\alpha = 0$, the routing strategy recovers the classic ER strategy. When $\alpha = 1$, the path with minimum sum queue length of nodes is chosen and thus it is just equivalent to the GD routing strategy.

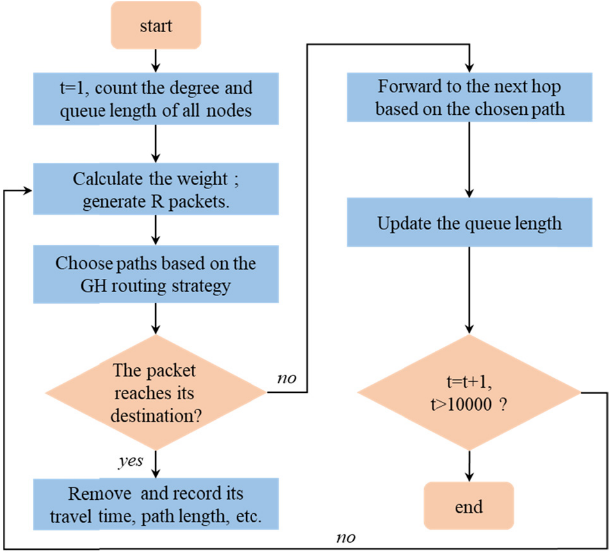

FIGURE 1. (Color online) The workflow of the routing process.

As has been analyzed in previous section, we cannot know what is the most appropriate relative weight of queue length and the degree from intuition. Therefore, we make the tunable parameter α to balance their influence to the network performance. Unlike previous methods to make complex designs or create dizzying functions, we just take three decisive factors (i.e. path length, degree and queue length) into consideration. The design is simple, so it is practical and can be easily implemented in real networks. Moreover, we catch the factors that matter to routing efficiency and weigh their impact, so the network performance could be promoted.

The detailed procedure of the routing process is shown in Fig. 1. We first need to count the degree and queue length of all nodes. Secondly, we should calculate the linear weighted sum of each node and generate R packets at each step. Next, based on the weights of all nodes, we apply the SP routing strategy to calculate the optimal paths as defined in the formula (1). One can find out that our GH routing strategy can be transformed into SP routing strategy. So the complexity of the GH routing strategy is extremely low. Then, a packet will be routed based on the chosen path. The queue length of the corresponding nodes will be updated every time step after the packets is forwarded from the predecessor nodes. Once a packet arrives at its destination, it will be removed from the system and its routing information such as packet travel time, path length will be recorded. In practice, we can set a relative longer simulation time t to let the network to reach a steady state, for example, we can let $t = 10000$. The repeated routing process will go on until the simulation ends.

In order to describe the traffic congestion, we use the order parameter [30]

$$\eta(R) = \lim_{t\to\infty} \frac{C}{R} \frac{\langle \Delta N_P \rangle}{\Delta t}, \tag{4}$$

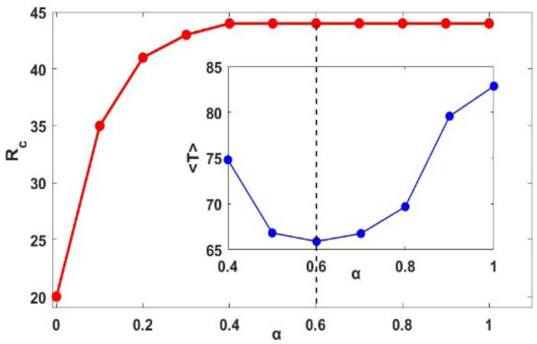

FIGURE 2. (Color online) The critical packet generation rate R_C vs α. The inset depicts the average packets travel time $\langle T \rangle$ vs α under $R = R_C = 44$. The network size $N = 600$ and average degree $\langle k \rangle = 4$.

where $\Delta N_P = N_P(t + \Delta t) - N_P(t)$, $\langle \cdots \rangle$ indicates the average over time windows of width Δt, and $N_p(t)$ is the total number of packets within the network at time t. C is the average processing capacity over all nodes (here, as has been assumed $C = 1$). There is a critical value R_c indicating the phase transition from free-flow to jamming. When $R < R_c$, due to the balance of created and removed packets, the total number of packets in the network slightly fluctuates around a constant, and η is around zero. However, when $R > R_c$, the packets accumulate continuously in the network, thus traffic congestion will occur and η will be a constant larger than zero. Therefore, R_c can be used to measure the traffic capacity of networks.

IV. SIMULATION RESULTS

In this section, we present simulation results when the packets are delivered using the ER strategy, the GD routing strategy, and our GH routing strategy respectively. We choose the state-of-the-art ER strategy and GD routing strategy as a baseline to evaluate the performance of our GH routing strategy.

A. DETERMINE THE OPTIMAL PARAMETER FOR GH

First, we investigate the performance with respect to the weight parameter α for the GH routing strategy. Fig. 2 depicts the results in terms of both the traffic capacity R_C and the average packets travel time $\langle T \rangle$ with the network size $N = 600$ and average degree $\langle k \rangle = 4$. Fig. 2 shows the traffic capacity R_C is relatively enhanced by increasing α when α is smaller than a specific value, approximately 0.4, and then it remains steady at 44. With the increasing of α, the dynamic queue length property takes more weight. Thus, packets will bypass the heavily loaded nodes, which brings about more evenly distributed load. Since all nodes share the same forwarding capacity, more evenly distributed load among nodes means less probability of jamming in the network. Therefore, the traffic capacity is enhanced by increasing the value of α. However when α is larger than 0.4, the dynamic queue length information takes adequate weight, and the traffic capacity cannot be further enhanced by merely increasing the value of α. The inset of Fig. 2 depicts the average travel time of packets $\langle T \rangle$ for different α under which the optimal traffic capacity can be achieved. $\langle T \rangle$ gets minimum value when $\alpha = 0.6$. Since the routing strategy can both achieve the maximum traffic capacity and the minimum average packets travel time when $\alpha = 0.6$. We can conclude that $\alpha = 0.6$ is the best choice, and it will be used in the following simulations.

To explain the phenomenon that different α results in different $\langle T \rangle$, we make further investigations on the average path length of removed packets and queue length of nodes. All the statistical information is obtained when the system reaches a balanced state, in which the newly generated packets approximately equal to removed packets at every time step and the total number of packets in the network remains stable. Fig. 3(a) shows that the probability distribution of path length approximately follows a Poisson distribution. The inset of Fig. 3(a) depicts that the GH routing strategy has slightly shorter average path length $\langle pl \rangle$ than that of the GD routing strategy. As can be seen from Fig. 3(b) and the inset of Fig. 2, the normalized average queue length $\langle ql \rangle$ and the normalized variance of queue length $D(ql)$ shares the same trend with $\langle T \rangle$ as functions of α. When $\alpha = 0.6$, the minimum $\langle ql \rangle$ and the minimum $D(ql)$ is valued. Compared with the GD routing strategy, the average queue length of nodes under the GH routing strategy is reduced by more than 23%. From the above discussions, we can conclude that the decreasing of $\langle T \rangle$ is mainly caused by a lighter load in nodes and a more even queue length distribution, which is essential for the packets to reduce the waiting time in a queue. Shorter path length implies that the packets have fewer nodes to pass through, which also contribute to smaller $\langle T \rangle$.

B. PERFORMANCE OF GH UNDER DIFFERENT TOPOLOGY

In order to evaluate our GH routing strategy more thoroughly, we investigate its performance in different network topology. Fig. 4(a) and Fig. 4(b) show that the traffic capacity is enhanced by increasing the network size N or the average degree $\langle k \rangle$ under three routing strategies. According to the simulation results, our GH routing strategy achieves the same traffic capacity as the GD routing strategy does, which is more than double of the ER strategy.

Fig. 5 shows the average packets travel time $\langle T \rangle$ vs the average degree $\langle k \rangle$, and vs the network size N under the GD and GH routing strategy with $R = R_c$. In Fig. 5(a), the average packets travel time $\langle T \rangle$ change with the average degree $\langle T \rangle$. From the inset of Fig. 5(a), one can see that the GH routing strategy can reduce $18\% - 23\%$ average packets travel time compared with the GD routing strategy. As shown in Fig. 5(b), the average packets travel time increases with the network size. The inset of Fig. 5(b) depicts that the GH routing strategy can reduce $18\% - 26\%$ average packets travel time compared with the GD routing strategy.

From the above results, one can be convinced that our GH routing strategy can be used in scale-free networks with different network scale and structure. That is to say, our routing strategy is highly efficient and universal.

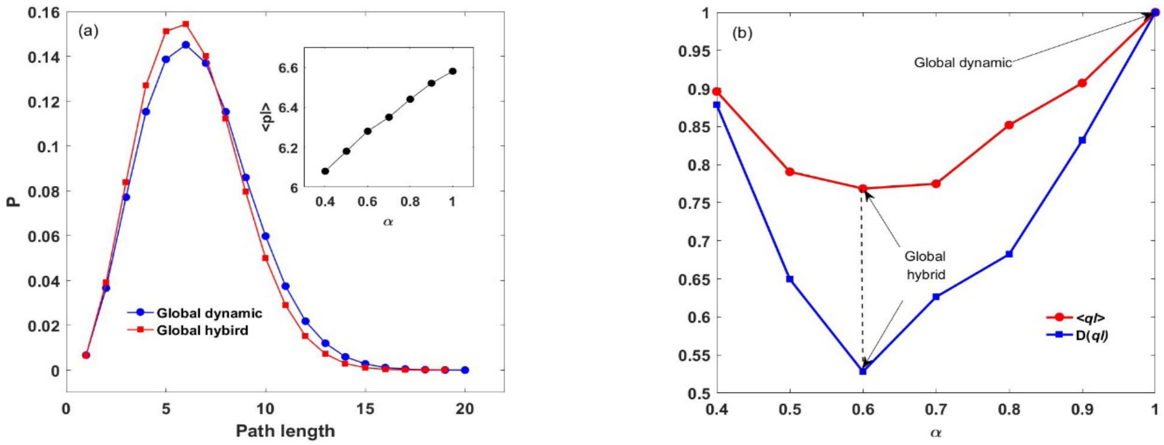

FIGURE 3. (Color online) (a) The probability distribution of path length for the GD routing strategy and the GH routing strategy. The inset depicts the average path length $\langle pl \rangle$ vs α. (b) Normalized average queue length $\langle ql \rangle$ and normalized variance of queue length $D(ql)$ vs α. Other parameters are network size $N = 600$, average degree $\langle k \rangle = 4$ and $R = R_C = 44$.

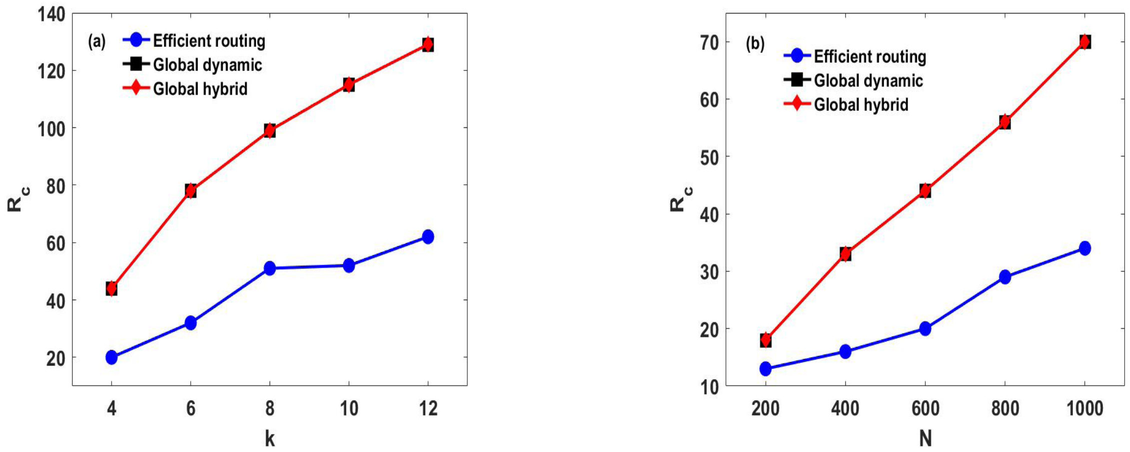

FIGURE 4. (Color online) (a) The traffic capacity R_c vs the average degree $\langle k \rangle$ with the same network size $N = 600$ under three different routing strategies. (b) The traffic capacity R_c vs network size N with the average degree $\langle k \rangle = 4$ for three different routing strategies.

C. GH WITH PERIODICALLY UPDATEING THE DYNAMIC INFORMATION

Because the queue length is changing at any time, hence it is a time-consuming process to update the dynamic queue length information and find routing paths at each time step. To make the routing strategy more practical, we introduce a time delay T_s for the update of the global queue length information and the routing paths.

We first investigate the evolution of total packet number N_p for different R with a time delay of $T_s = 20$. One can see from Fig. 6 that although the queue length is updated every 20 time steps, the traffic capacity remains at $R_C = 44$.

Next, we explore the traffic capacity with different time delay under the GD and GH routing strategy. According to Fig.7, one can find out that the traffic capacity is irrelevant to time delay T_s when T_s is no more than 100 time steps for both routing strategies. What is more, longer time delay T_s results in bigger N_p when the network reaches a steady state. Fig. 7(a) shows that under the GD routing strategy, N_p increases quickly to a maximum and then decrease to a steady state. Because at the beginning of the simulation, there is no packets in each node. Thus, the GD routing strategy degenerates into the shortest path routing strategy, which has a small traffic capacity. Therefore, the network comes into a congestion state rapidly and a large amount of packets accumulate in the network until the GD routing strategy takes control. Fig. 7(b) shows that the network evolution process under our GH routing strategy is different. That is because at the beginning of transportation, our GH routing strategy degenerates into the ER strategy, which has a relatively high traffic capacity. Hence, N_p increases slowly and then reaches a steady state.

We also investigate the impact of time delay T_s on the average packets travel time $\langle T \rangle$ under the GD routing strategy and the GH routing strategy. In Fig. 8, one can find that the probability distribution of packets travel time for different T_s

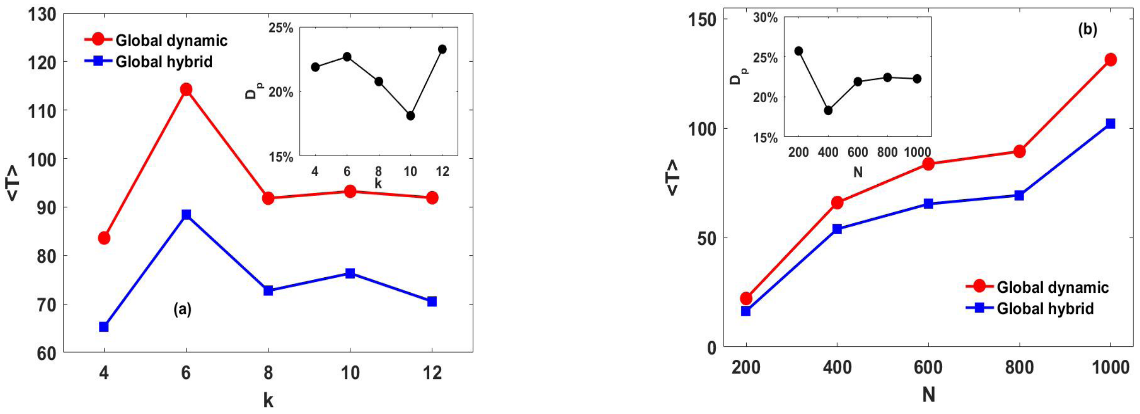

FIGURE 5. **(Color online) (a) The average packets travel time $\langle T\rangle$ vs the average degree $\langle k\rangle$ with the same network size $N = 600$ under $R = R_c$. The inset depicts the percentage of reduced $\langle T\rangle$ of the GH routing strategy compared with the GD routing strategy. (b) The average packets travel time $\langle T\rangle$ vs network size N with the average degree $\langle k\rangle = 4$ under $R = R_c$. The inset depicts the percentage of reduced $\langle T\rangle$ of the GH routing strategy compared with the GD routing strategy.**

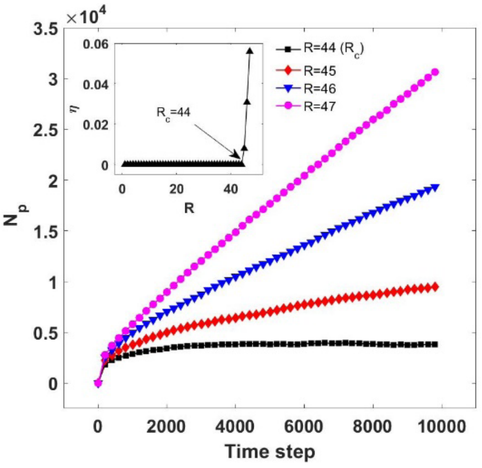

FIGURE 6. **(Color online) Evolution of N_p for different packet generation rate R with time delay $T_s = 20$. The order parameter η vs R is depicted in the inset of the Figure.**

follows a Poisson distribution under two routing strategies. Bigger T_s results in longer $\langle T\rangle$ under both routing strategies. Moreover, the GH routing can achieve more than 21% lower $\langle T\rangle$. Since our GH routing strategy not only consider the dynamic information but also combine the static network structural information, it is less sensitive to the time delay and longer T_s makes it have a greater decline in $\langle T\rangle$ compared with the GD routing strategy. The decline of $\langle T\rangle$ can be up to 40% when $T_s = 100$ with the network size $N = 600$ and average degree $\langle k\rangle = 4$.

We further analyze the reason why the average packets travel time $\langle T\rangle$ increases with the time delay T_s. We first investigate the queue length of nodes when the system reaches a balanced state. Nodes with higher degree tend to have bigger queue length, so we investigate the average queue length $\langle q(k)\rangle$ with degree k. As can be seen from Fig. 9, $\langle q(k)\rangle$ increases with T_s for both routing strategies. This is consistent with that the total number of packets increased with T_s. As one can see from Fig. 9(a), hub nodes tend to have longer queue length under the GD routing. However, Fig. 9(b) shows that the GH routing has more well-distributed queue length distribution and lighter loads compared with GD routing.

Finally, we analyze the probability distribution of the path length of removed packets. As can be seen from Fig. 10, the probability distribution of path length approximately follows a Poisson distribution for different T_s under two different routing strategies. The inset of Fig. 10 depicts that the average path length increases slightly with T_s under both routing strategies. Moreover, the average path length of the GH routing strategy is relatively smaller than that of the GD routing strategy.

From the discussions above, we can draw the conclusion that although introducing the time delay will increase the average packets travel time, which mainly comes from the heavier load and longer waiting time in the nodes, our GH routing can achieve much smaller average packets travel time than that of GD routing strategy.

D. APPLY GH TO DATA CENTER NETWORK

To illustrate the universality of our GH routing strategy in scale-free networks, both real and synthetic. In this part, we will give a practical example of applying the GH routing strategy to the data center network. Gyarmati *et al.* [36] proposed a data center architecture that is inspired by a scale-free network. It constrains the degree of the network's nodes to satisfy the physical restrictions of network devices. Such design shows desirable properties, e.g. short distances between the nodes, high error tolerance and incremental extension feature.

First, we use the proposed mechanism in [36] to generate a topology consists of 4000 nodes. Among them, 1980 nodes are commodity switches with 48 ports, and the rest are servers with 2 ports connected to the switches, together they form a scale-free network under physical constrains. As the assumptions have been made in previous simulations, there

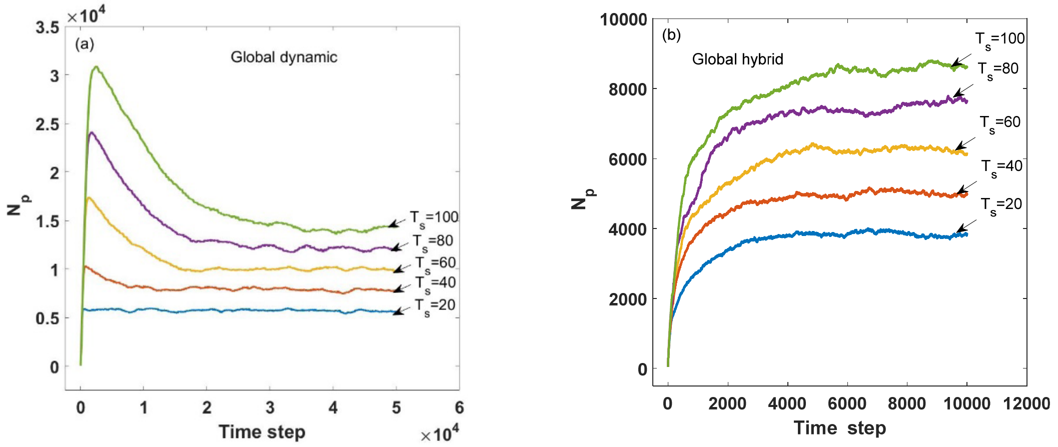

FIGURE 7. (Color online) Evolution of N_p for different time delay T_s. The traffic capacity remains at $R_c = 44$ for all T_s under two routing strategies. (a) GD routing strategy and (b) GH routing strategy. Other parameters are network size $N = 600$ and average degree $\langle k \rangle = 4$.

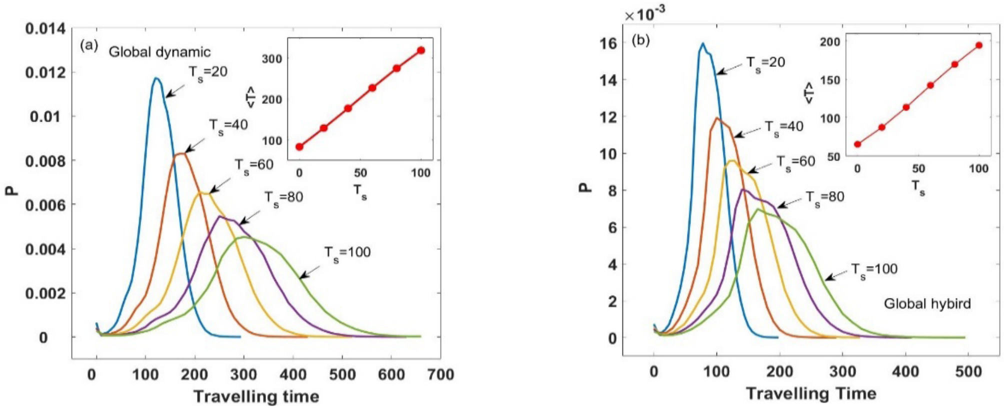

FIGURE 8. (Color online) The probability distribution of packets travel time for different T_s under two different routing strategies. The inset depicts the average packets travel time $\langle T \rangle$ vs the time delay T_s. (a) GD routing strategy. (b) GH routing strategy. The network size $N = 600$, average degree $\langle k \rangle = 4$ and $R = R_c = 44$.

are R packets generated from the servers, with randomly selected sources and destinations and then they are forwarded by the switches based on the GH routing strategy.

Simulations shows that the traffic capacity will not be affected by the time delay T_s of dynamic information under both GD and GH routing strategy, even when T_s is as large as 100 time step. The traffic capacity of these two routing strategy remain at $R_c = 151$. At the same time, the ER strategy can only achieve $R_c = 55$, which is far lower than our GH and the GD routing strategy. Fig. 11(a) depicts the evolution of total packet number N_p with different time delay under the GD and GH routing strategy when $R = R_c = 151$. We analyze the average packets number $\langle N_p \rangle$ when the network reaches a balanced state. From the inset of Fig. 11(a), one can see that $\langle N_p \rangle$ increase with the updating delay T_s and GH has much smaller $\langle N_p \rangle$ compared with GD routing strategy. Fig. 11(b) depicts the probability distribution of packets travel time for different T_s under both routing strategies. The inset of Fig. 11(b) shows that the average packets travel time $\langle T \rangle$ increase with the time delay T_s. We can find out that the GH routing strategy can achieve much smaller $\langle T \rangle$. When $T_s = 100$, GD has more than five times larger average packets travel time compared with our GH routing strategy. Because more packets are piled up waiting for transmission under GD routing strategy just as Fig. 11(a) shows, which results in longer travelling time for every packet.

From the above discussions, one can see that our GH routing strategy can achieve high traffic capacity in real data center network. In addition, compared with GD routing strategy, the decline of average packets travel time is extremely considerable and the decline can be up to more than 80% when the updating time delay equals 100 time steps. Therefore, we may say that our GH routing strategy is efficient, practical and can be applied to real scale-free networks to enhance the network performance.

E. SIMULATION SUMMARY

According to the above simulation results, we summary the GH routing strategy in this part.

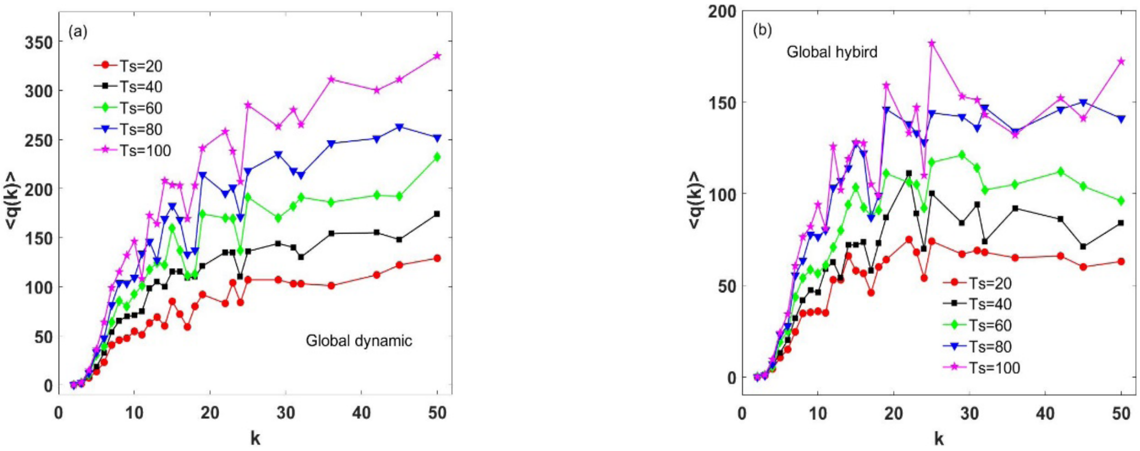

FIGURE 9. (Color online) Average packet number in nodes with degree k vs node degree k with different T_S under two different routing strategies. (a) GD routing strategy. (b) GH routing strategy. The network size $N = 600$, average degree $\langle k \rangle = 4$ and $R = R_c = 44$.

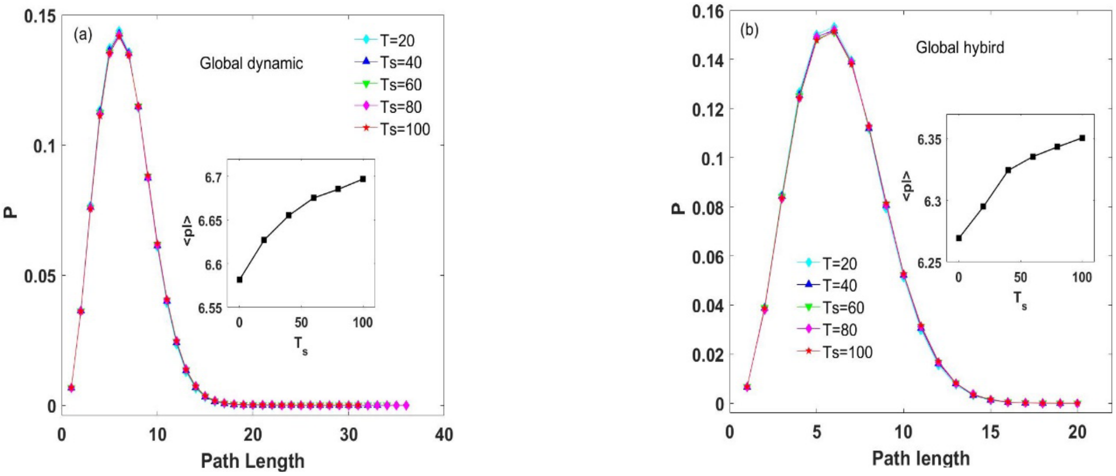

FIGURE 10. (Color online) The probability distribution of path length for different T_S under two different routing strategies. (a) GD routing strategy. (b) GH routing strategy. The inset depicts the average path length $\langle pl \rangle$ vs T_S. The network size $N = 600$, average degree $\langle k \rangle = 4$ and $R = R_c = 44$.

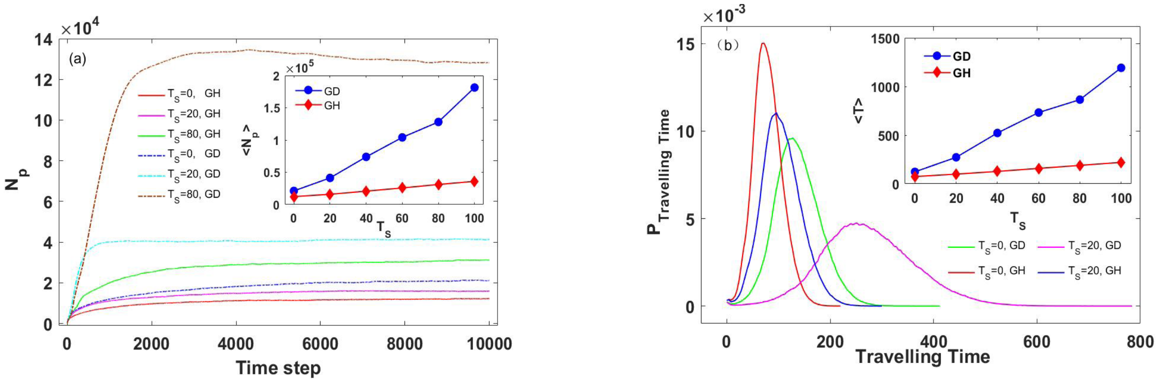

FIGURE 11. (Color online) (a) Evolution of N_p for different T_S under GD and GH routing strategies. The inset depicts the average packets number $\langle N_p \rangle$ vs T_S. (b) The probability distribution of packets travel time. The inset depicts the average packets travel time $\langle T \rangle$ vs T_S.

First, we find the optimal parameter for the GH routing strategy and analyze the influences of different weight parameters to the network performance.

Then, we investigate the performance of our GH routing strategy in different network scale and structure. Simulation results show that our GH routing strategy can provide the same traffic capacity as the GD routing strategy does, which is more than twice as high as the ER strategy. What is more, our GH routing strategy can achieve about 20% smaller average packets travel time than that of the GD routing strategy.

Next, we also investigate the situation that the dynamic queue length information is collected and updated periodically. With the increasing of updating time delay T_s, the traffic capacity remains the same, but the total number of packets in the network, and the average packets travel time will increase. The increment of average packets travel time is mainly induced by longer waiting time in the nodes toward the destination. Longer time delay makes the GH routing have a greater decline in the average packets travel time compared with the GD routing strategy. The decline of $\langle T \rangle$ can be up to 40% when $T_s = 100$ with the network size $N = 600$ and average degree $\langle k \rangle = 4$.

Finally, to illustrate the practicability of our GH routing strategy, we apply it to a large scale data center network. And simulation results show that our GH routing strategy is practical and efficient.

V. CONCLUSION

Integrating the dynamic queue length information and the static degree information, we propose a GH routing strategy for scale-free networks. Under this strategy, the traffic capacity can achieve as high as the GD routing strategy does, which is more than double of the efficient routing strategy. Moreover, the GH routing strategy can bring about more well-distributed queue length distribution and a lighter load in nodes. Therefore, our GH routing strategy can reduce the average packets travel time. We investigate its performance in both synthetic BA scale-free networks and real data center network. Simulation results show that our GH routing strategy is efficient, universal, practical and can improve the network performance in both cases.

Since the GH routing strategy can not only achieve high traffic capacity but also obtain short average packets travel time, it can be applied to enhance the network performance in many real-world systems other than data center network. In the future work, we may explore to apply our GH routing strategy to some other real networks, such as the Internet, social networks, and city transport networks.

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