Generalized minimum information path routing strategy on scale-free networks

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This paper presents a new routing strategy by introducing a tunable parameter into the minimum information path routing strategy we proposed previously. It is found that network transmission capacity can be considerably enhanced by adjusting the parameter with various allocations of node capability for packet delivery. Moreover, the proposed routing strategy provides a traffic load distribution which can better match the allocation of node capability than that of traditional efficient routing strategies, leading to a network with improved transmission performance. This routing strategy, without deviating from the shortest-path routing strategy in the length of paths too much, produces improved performance indexes such as critical generating rate, average length of paths and average search information.

Keywords: scale-free networks, routing strategy, minimum information path

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1. Introduction

Due to the rapid development of many real networks, e.g., WWW, Internet and traffic networks, it is of great significance to enhance the transmission performance of underlying networks. Generally, network transmission performance can be improved in two ways: optimizing network structure and designing a better routing strategy.[1−5] As it will cost too much to change the structure of a large-scale network and it is also difficult to implement, most works have been devoted to the development of effective routing strategies. Traditionally, the shortest-path routing (SR) strategy has been widely applied in many network systems. However, it is found that the heterogeneity of node degree in a network leads to the intense heterogeneity of node betweenness centrality, indicating that information packets tend to pass through a few centralized nodes with high node betweenness centrality.[6] As a result, when there is heavy network traffic, congestion will firstly occur on centralized nodes and then spread to other nodes, leading to the network eventually jamming. In order to enhance network transmission capacity, several routing strategies have been proposed and they can be classified into three types: routing strategy based on global information, local information and dynamical information of networks.

Based on the global information of a network structure, the efficient routing (ER) strategy was proposed,[7] as well as a method that changes the weight of links in order to decrease the maximum node betweenness,[8] or bypasses the centralized nodes to find an alternative shortest path.[9] The local information applied in the routing strategy can be neighbour information,[10] next-neighbours information,[11] as well as pheromone information.[12] By taking dynamic information about the traffic process, such as neighbours' queue length[13] and neighbours' waiting time,[14] into account, the transmission capacity of a network can also be improved. In addition, some new routing strategies, such as compact routing and greedy routing in a hidden metric space, have been studied.[15,16]

Recently, we reported that when a random walker searches a fixed path on a network, the mean first hitting time is proportional to the product of the de-

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gree of nodes on the path.[17,18] Inspired by this result, we present the minimum information path routing (MIPR) strategy, which selects the path with the minimum node degree product.[19] When the node capability of packet delivery is proportional to the node degree, the simulation results show that the node traffic load is proportional to its degree, with the cost of a slight increase of path length. It is obvious that the MIPR strategy can lead to a network with optimal transmission performance when the node capability of packet delivery is proportional to its degree. However, in some networks, all nodes have the same packet delivery capability, so the MIPR strategy cannot be applied to such networks directly. In this paper, by attempting to distribute the traffic load to the nodes according to their various allocation of packet delivery capability, we propose a new routing strategy based on the global topological information in which a tunable parameter can be adjusted according to a specific allocation of node capability for packet delivery. This new routing strategy is called the generalized MIPR (GMIPR) strategy.

In this paper, firstly, we give the analytical solution of mean first hitting time for searching the fixed path on a network. This conclusion uncovers the relationship between the transmission path and the degree of nodes on the path. A part of the solution is equivalent to the average search information in network. Secondly, we describe our routing algorithm based on the Dijkstra algorithm. Furthermore, the proposed GMIPR strategy is compared with the SR strategy and the ER strategy in a Barabási–Albert (BA) network. Performance indexes such as the critical generating rate, the node betweenness centrality, the average length of paths and the average search information, are presented for the simulation results. In the discussion, we construct the two-node capability of packet delivery allocation schemes to compare the routing strategies: all nodes have the same node capability and node capability is proportional to its degree. We find that our GMIPR strategy can lead to a network with a larger transmission capacity in comparison with the traditional SR strategy and ER strategy.

This paper is organized as follows. In Section 2 we give the derivation of mean first hitting time for finding a fixed path and the description of our routing algorithm. In Section 3 we discuss the simulation results of the GMIPR strategy and a conclusion is offered in Section 4.

2. Routing strategy based on searching information

In order to describe the difficulty of navigation in different networks, reference [20] defined the "search information" S. For any path $p(i \to j)$ from node i to node j, we calculate the probability $P\{p(i \to j)\}$ for following the given path if one chooses any new direction with equal probability without prior knowledge

$$P\{p(i \to j)\} = \frac{1}{k_i} \prod_{n \in p(i \to j)} \frac{1}{k_n - 1}, \tag{1}$$

where n represents the node on the path from node i to the last node before the target node j. The denominator $k_n - 1$, instead of k_n, takes the information we gain by following the path into account and, therefore, the number of existing edges are reduced by one. Thus, "search information" can be defined as the total information needed to identify one of all the degenerate paths between node i and node j

$$S(i \to j) = -\log_2 \left(\sum_{p(i \to j)} P\{p(i \to j)\} \right), \tag{2}$$

where the sum runs over all degenerate paths connecting node i with node j. A large $S(i \to j)$ indicates that one needs many yes/no questions to locate j. The existence of many degenerate paths will be reflected in a small S and consequently in easy goal-finding. Inspired by $S(i \to j)$, we define the average search information $S_{\rm ave}$ to estimate the average information needed to construct the total fixed routing table as

$$S_{ave} = \frac{1}{N(N-1)} \sum_i \sum_j S(i \to j), \tag{3}$$

where N is the network size. So $N(N-1)$ is the number of paths in the routing table. The less $S_{\rm ave}$ is, the easier for a random walker to navigate in the networks is. Reference [21] quantified the information associated with locating specific city network addresses by introducing "search information".

Equation (1) indicates that the probability of searching a node is relevant to the product of the node degree on the searching path. The more the product of the node degree on the path is, the more difficult for a node to be searched is. We also provide the theoretical base of the search information from the aspect of mean first hitting time to find a fixed path through

random walks in a network.[17,18] Based on this theoretical base, we propose the GMIPR routing strategy. To begin with, in a simple connected network $G(V,E)$, suppose that the number of nodes is $|V|=n$ and the number of links is $|E|=m$. The adjacent matrix of the network is denoted as $A=(a_{ij})_{n\times n}$ and the transition probability matrix of the walker can be expressed as $P=(a_{ij})_{n\times n}=DA$ where D is a diagonal matrix. We study the problem of searching for a fixed path $R(u\rightarrow v)$ on networks through random walks, in which $u=\varepsilon_0$, $v=\varepsilon_l$ and $\varepsilon_i\varepsilon_{i+1}$ $(0\leq i\leq l-1)$ is the network link. The length of path R is l. We suppose the t-step trace for a random walker is $W(t)=\sigma_0\sigma_1\ldots\sigma_t$ $(\sigma_i\in V, 0\leq i\leq t)$. If $R\subseteq W(t)$, it means that the walker has found path R. Let $T=\tau$ be the first hitting time for a random walker and the first hitting probability is $f(t)=\mathrm{Prob}\{T=t\}$. In order to calculate $f(t)$, we calculate conditional probability $\theta(t)$ first. If a random walker starts from node s and finally reaches node u, the probability $\theta(t)$ that this walker finds the first node of path R in t-steps can be expressed as

$$\theta(t)=P_0\sum_{r=1}^{t-l-1}\left(p_{su}^{(r)}-\theta(r)\right)\cdot p_{vu}^{(t-l-r)}, \qquad (4)$$

where $P_0=p_{\varepsilon_0\varepsilon_1}\ldots p_{\varepsilon_{l-1}\varepsilon_l}$, $p_{ij}^{(m)}$ is m-steps transition probability from node v_i to node v_j.

We suppose that the generating function of $p_{ij}^{(t)}$ is $\Psi_{ij}(x)$ where $\Psi_{ij}(x)=\sum_{t=0}^{\infty}p_{ij}^{(t)}x^t$ and the generating function of $\theta(t)$ is $\Theta(x)=\sum_{t=0}^{\infty}\theta(t)x^t$. Using the t-step transition probability expressed in Ref. [22]: $p_{ij}^{(t)}=2m/k_j+\sum_{k=2}^{n}\lambda_k^t\xi_{ki}\xi_{kj}\sqrt{k_j/k_i}$, we can obtain

$$\Psi_{ij}t(x)=\frac{2m}{k_j(1-x)}+\sum_{k=2}^{n}\frac{1}{1-\lambda_k x}\xi_{ki}\xi_{kj}\sqrt{\frac{k_j}{k_i}}, \qquad (5)$$

where λ_k are eigenvalues of matrix $Q=D^{-1/2}PD^{1/2}$, and ξ_k are corresponding eigenvectors. Consequently, $\Theta(x)$ can be expressed as

$$\Theta(x)=\frac{P_0x^l\Psi_{su}(x)\Psi_{vu}(x)}{1+P_0x^l\Psi_{vu}(x)}. \qquad (6)$$

Furthermore, the first hitting probability $f(t)$ can be computed as:

$$\begin{aligned}f(t)&=\mathrm{Prob}\{T=t|\sigma_0=s\}\\&=\left[p_{su}^{(t-l)}-\Theta(t-l)\right]P_0,\quad (t>l).\end{aligned} \qquad (7)$$

From Eqs. (5)–(7), we derive the mean first hitting time $\langle T\rangle$ as follows:

$$\begin{aligned}\langle T\rangle&=\sum_{t=0}^{\infty}t\cdot f(t)\\&=2m\prod_{i=1}^{l-1}k_i+2m\sum_{k=2}^{n}\frac{1}{1-\lambda_k}\left[\frac{\xi_{kv}\xi_{ku}}{\sqrt{k_vk_u}}-\frac{\xi_{ks}\xi_{ku}}{\sqrt{k_sk_u}}\right],\end{aligned} \qquad (8)$$

where the first part is proportional to the product of the degree of nodes on the fixed path except for the initial and terminal nodes, and the second part is related to the network structure. Thus we find that the mean first hitting time for a random walker is proportional to the product of the degree of nodes on the path. In order to minimize the search information, we proposed the MIPR strategy in Ref. [19]. It chooses a path between the initial node and the terminal node that obtains the minimum product of all nodes' degree. As a result, path P_{opt}, which is the optimal path from node v_i to node v_j, should satisfy the following condition:

$$\Omega(P_{\mathrm{opt}}(v_i\rightarrow v_j))=\min\prod_{m=0}^{n-1}k_m, \qquad (9)$$

where n is the path length and k_m is the node degree on the path P_{opt}. Simulation results indicate that when the node capability of packet delivery is proportional to its degree, the network can obtain its maximum transmission capacity. Considering the various relationships between the node capability and its degree, we propose a new routing strategy, called the GMIPR strategy, which can be described as follows: among the paths between node v_i to node v_j, we select the path that satisfies the following condition:

$$\Omega(P_{imp}(v_i\rightarrow v_j))=\min\sum_{m=0}^{n-1}(\ln(k_m))^{\alpha}, \qquad (10)$$

where α is a tunable parameter from $(-\infty,\infty)$. If there is more than one path between a pair of nodes meeting Eq. (10), then we randomly select one of them and put this path in the routing table. When $\alpha=0$, the GMIPR strategy recovers the SR strategy. When $\alpha=1$, the MIPR strategy is recovered.

Based on the Dijskrta algorithm, the GMIPR strategy algorithm can be easily obtained. Suppose the set of nodes in the network is V, the adjacent matrix of the network is deg and the network size is N. If a link between node v_i and node v_i exists, $deg[i,j]$

equals k_j which is the degree of node v_j; otherwise $deg[i,j]$ equals ∞. We use D to denote the set in which nodes already have a routing path directing them to the initial node v_n and $pdt[i]$ is the sum of logarithm of node degree on the routing path from node v_n to node v_i ($n \neq i$). The algorithm can be described as follows:

Step 1 Suppose that D is vacant. Let $pdt[i] = (\mathrm{Ln}(k_n))^{\alpha} + deg[n,i]$, where $v_i \in V - \{v_n\}$.

Step 2 Select node v_j which satisfies the condition: $pdt[j] = \min\{pdt[i] | v_i \in V - D - \{v_n\}\}$, and $D = D \cup \{v_j\}$.

Step 3 If there is node v_k which belongs to the set $V - D - \{v_n\}$ and also satisfies the condition: $pdt[j] + deg[j,k] < pdt[k]$, then we change the $pdt[k]$ to $pdt[k] = pdt[j] + deg[j,k]$.

Step 4 Repeat Steps 2 and 3 $(N-1)$ times until all nodes in the network have their routing path directing them to node v_n.

Step 5 Choose a different initial node v_n and repeat Steps 1–4 N times until the routing table of the network has been established.

3. Results and discussions

Considering the fact that most of the realistic networks are of a scale-free nature, here we focus on the networks with scale-free topology, for instance, the famous BA network with an exponent of degree distribution $\gamma = 3$.[23] The size of the network is set to $N = 1500$ and the parameters of the model are set to be $m_0 = m = 2$ (hence the average connectivity of the network is $\langle k \rangle = 4$). Each node of the network acts as both a host and a router at the same time. We also assume that each node possesses a queue of infinite length and that the FIFO (first in first out) discipline is applied at each queue. At each time step, there are R information packets generated in the network, with randomly chosen sources and destinations. The allocations of node capability of packet delivery, which is the largest number of information packets that a node can forward to other nodes in a time step, are assumed to be two schemes in the following discussion. In the first scheme, every node has the same capability of packet delivery, i.e. $C_i = 5$; while in the second scheme, the node capability of packet delivery is proportional to the node degree, i.e. $C_i = k_i$.

3.1. Network transmission performance

In order to evaluate the load distribution in nodes with the same degree, similar to the definition of betweenness centrality for the nodes of the same degree in Ref. [7], we define the average routing betweenness centrality $B(k)$ for nodes of same degree k in a scale-free network as

$$B(k) = \frac{1}{N_k} \sum_{s \neq t, k_i = k} \sigma_{st}(i), \tag{11a}$$

$$\sigma_{st}(i) = \begin{cases} 1, & v_s \to v_t \quad \text{pass} \quad v_i, \\ 0, & v_s \to v_t \quad \text{does not pass} \quad v_i, \end{cases} \tag{11b}$$

where $N(k)$ denotes the number of nodes with degree k. A proper routing strategy should make the traffic load in the networks (revealed by $B(k)$) proportional to the node capability of packet delivery. That is to say, when the nodes have the same packet delivery capability, the ideal situation is $B(k) = \text{const}$ and the magnitude of $B(k)$ should also be relatively low; when the packet delivery node capability is proportional to the node degree, the ideal $B(k)$ should be also proportional to the node degree. Under these circumstances, the network can obtain maximum transmission capacity.

Figure 1 shows the relationship between $B(k)$ and k with varying parameters when the network implements the ER strategy and the GMIPR strategy separately. The ER strategy requires the path p_{ij} between node i and node j satisfying $p_{ij} = \min \sum_{n=0}^{l} k_n^{\beta}$, in which k_n is the degree of node on the path and β is a tunable parameter. As shown in Fig. 1(a), when the ER strategy is implemented in the network and $\beta = 0.4$, $B(k)$ is proportional to k. This result suggests that if the packet delivery node capability is proportional to their degree, $\beta = 0.4$ is the optimal parameter value. When β increases, in comparison with curves for $\beta = 0.6$ and $\beta = 0.8$, the curves of $B(k)$ for $\beta = 1$ and $\beta = 1.2$ have relatively lower magnitude. Furthermore, in comparison with curve for $\beta = 1.2$, the curve of $B(k)$ for $\beta = 1$ performs better at the nodes with higher degree, so we deduce that when all the nodes have the same packet delivery capability, $\beta = 1$ is the corresponding optimal parameter value. This conclusion is in accordance with the optimal parameter value pointed out in Ref. [7]. However, when $\beta = 1$, $B(k)$ exhibits a similar Poisson distribution and $B(k)$ is very low for nodes with high degree, which

means that the nodes with high degree are seldom used in the packet delivery process and traffic load mainly focuses on the nodes with a degree of around 15. Therefore, the transmission capacity of a network can be improved with another routing strategy, which can make use of the nodes with a high degree and a low degree simultaneously.

The distributions of $B(k)$ with varying parameters under our GMIPR strategy are displayed in Fig. 1(b). Similar to the same discussion above, we infer that $\alpha = 1$ is the optimal parameter value when the node capability of packet delivery is proportional to their degree and when all nodes have the same packet delivery capability, $\alpha = 1.8$ is the optimal parameter value. If $\alpha = 1.8$, $B(k)$ obtains the maximum value when $k = 20$ and decreases slowly when $k > 20$.

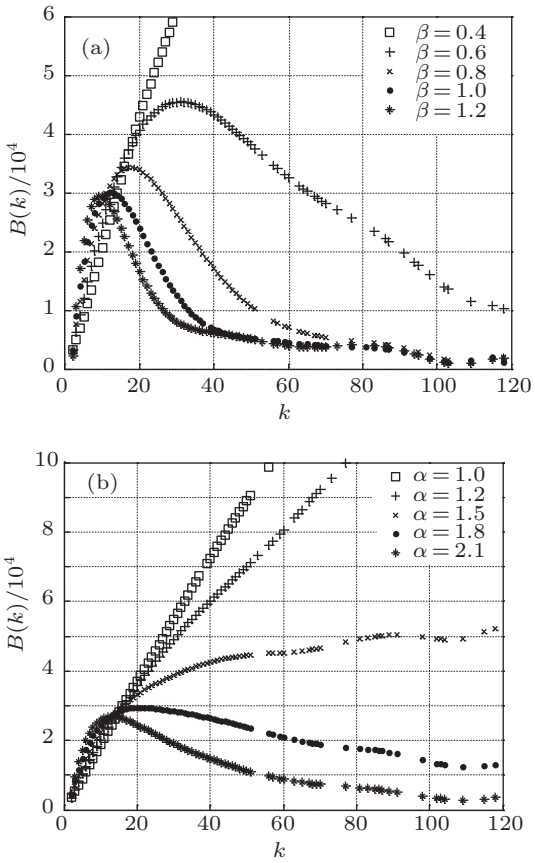


Fig. 1. The relationship between $B(k)$ and k with different routing strategy parameters: (a) the ER strategy and (b) the GMIPR strategy.

From the comparison of Fig. 1(a) with Fig. 1(b), we can see that the GMIPR strategy ($\alpha = 1.8$) utilizes the nodes with a high degree more frequently in comparison with the ER strategy ($\beta = 1$). Reference [7] pointed out that $B(k) \sim k^{\mu}$ when the SR strategy is applied. So when the nodes have the same packet delivery capability, the GMIPR strategy has a better load distribution performance than that of the ER and the SR strategies; when the node packet delivery capability is proportional to the node degree, the GMIPR strategy ($\alpha = 1$) and the ER strategy ($\beta = 0.4$) have a similar load distribution, which is better than that of the SR strategy because $B(k)$ of these two strategies is proportional to the node degree. The above discussion shows that the GMIPR strategy can lead to the network having a better load distribution in comparison with traditional routing strategies under circumstances of various distributions of node capability for packet delivery.

Furthermore, we discuss the network transmission performance under the GMIPR strategy based on indexes such as the critical generating rate $R_{\rm c}$, the average length of paths $L_{\rm ave}$ in the free-flow state and the average search information $S_{\rm ave}$. First, the transmission capacity of a network is measured by the critical generating rate $R_{\rm c}$ at which a continuous phase transition will occur from a free-flow state to a congested state. The critical generating rate $R_{\rm c}$ can be determined by observing the order parameter introduced in Ref. [24]

$$\eta(R) = \lim_{t\to\infty} \frac{1}{R} \frac{\langle \Delta W \rangle}{\Delta t}, \tag{12}$$

where $\Delta W = W(t + \Delta t) - W(t)$, $W(t)$ is the total number of packets in the network at time t, and $\langle \cdots \rangle$ indicates the average over time window of Δt. When $R < R_{\rm c}$, the network is in a free-flow state; then $\Delta W \approx 0$ and $\eta \approx 0$. When $R > R_{\rm c}$, ΔW increases with Δt. Therefore, a sudden change of $\eta(R)$ from zero to nonzero characterizes the onset of a phase transition from a free-flow state to a congested state, and the network transmission capacity can be measured through simulation by the maximal generating rate $R_{\rm c}$ at the phase transition point. Figure 2 shows the results of the critical generating rate $R_{\rm c}$ as a function of the routing parameter in networks for different routing strategies and node capability allocation schemes. We also obtain $R_{\rm c}$ values in a network with different sizes. Figure 2 shows the average performance over 10 independent runs.

When all the nodes have the same packet delivery capability, as shown in Figs. 2(a) and 2(b), $R_{\rm c}$ reaches its maximum value when $\alpha = 1.8$ with the GMIPR

strategy, and as the size of the network increases, the R_c value also increases. The optimal parameter of the ER strategy turns out to be $\beta = 1$, which is in accordance with the result deduced in Ref. [7]. When the capability of each node is proportional to its degree, figures 2(c) and 2(d) indicate that when $\alpha = 1$, the maximum R_c value is achieved and the GMIPR strategy is equivalent to the minimum information path routing strategy. As the equivalence of the results obtained through the observation of traffic load above, the optimal parameter for the ER strategy is $\beta = 0.4$. Therefore, in the following discussion, we will apply these optimal parameters in routing strategy according to the specific situation.

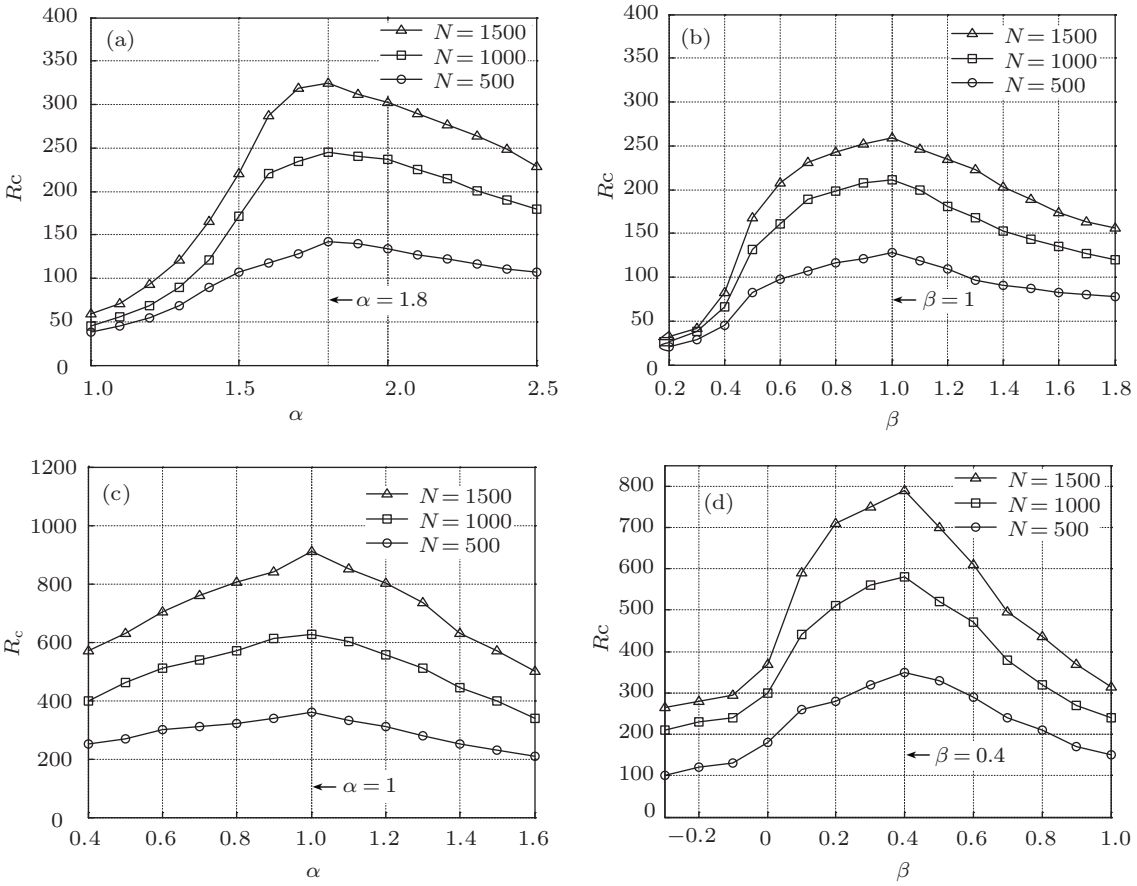


Fig. 2. The critical generating rate R_c versus routing strategy parameter in different network sizes ($N = 500$, $N = 1000$, $N = 1500$): (a) the GMIPR strategy and $C_i = 5$; (b) the ER strategy and $C_i = 5$; (c) the GMIPR strategy and $C_i = k_i$; (d) the ER strategy and $C_i = k_i$.

Table 1. The critical generating rate R_c, the average length of paths L_{ave}, the average search information S_{ave} under the SR strategy, the ER strategy and the GMIPR routing strategy, where $N = 1500$.

	$C_i = 5$			$C_i = k_i$		
	R_c	L_{ave}	S_{ave}	R_c	L_{ave}	S_{ave}
SR	16	4.22	13.96	372	4.22	13.96
ER	259	6.51	11.49	790	4.69	11.12
GMIPR	324	6.12	11.02	920	4.71	10.91

Table 1 shows the simulation results of three indexes under three different routing strategies and two-node capability allocations. The results indicate that when $C_i = 5$, the GMIPR strategy obtains the network with the highest R_c and the lowest S_{ave} among these routing strategies. In addition, L_{ave} under the GMIPR strategy increases 1.45 times in comparison with the SR strategy, while L_{ave} under the ER strategy increases 1.54 times. When $C_i = k_i$, although L_{ave} under the GMIPR strategy is slightly larger than that under the ER strategy, R_c and S_{ave} under the GMIPR strategy are better than those under the SR strategy and the ER strategy.

3.2. Network transmission performance and network size

In the following, we study the network transmission performance with different network sizes. A

routing strategy which elongates the path length unnecessarily may not be efficient for network communications.[9] So it is essential for a routing strategy to maintain the small-world phenomenon, i.e. $L_{\rm ave} \sim \ln N$. In Fig. 3, we show how $L_{\rm ave}$ (obtained by using three routing strategies) behaves with increasing network size. As one can see, the GMIPR strategy also maintains the small-world phenomenon. When $C_i = 5$, $L_{\rm ave}$ under the GMIPR strategy is lower than that under the ER strategy, while under condition of $C_i = k_i$, the ER strategy performs better than the GMIPR strategy.

In Fig. 4 we show the relationship between the critical generating rate $R_{\rm c}$ and the network size. They indicate that the network capacity under the GMIPR strategy revealed by $R_{\rm c}$ is larger than that under the SR strategy and the ER strategy under both conditions of $C_i = 5$ and $C_i = k_i$.

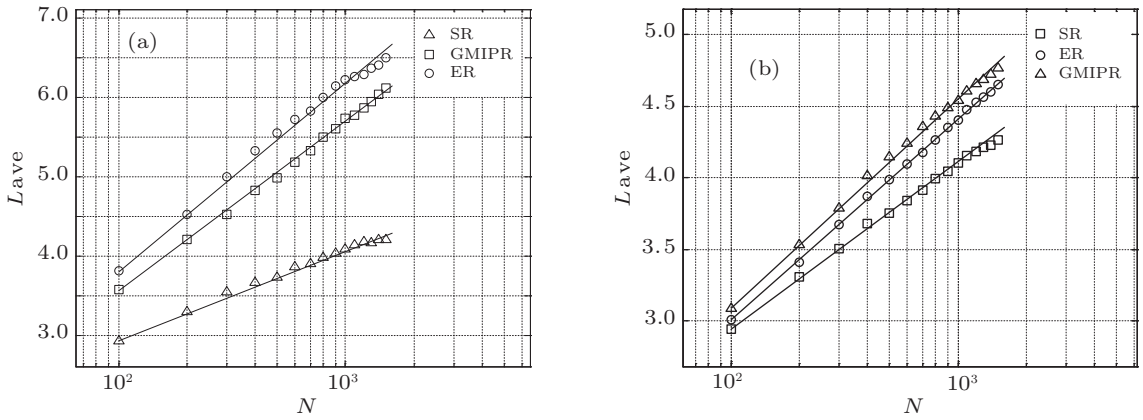


Fig. 3. The average length of paths $L_{\rm ave}$ versus the network size N under different routing strategies: (a) $C_i = 5$ and (b) $C_i = k_i$.

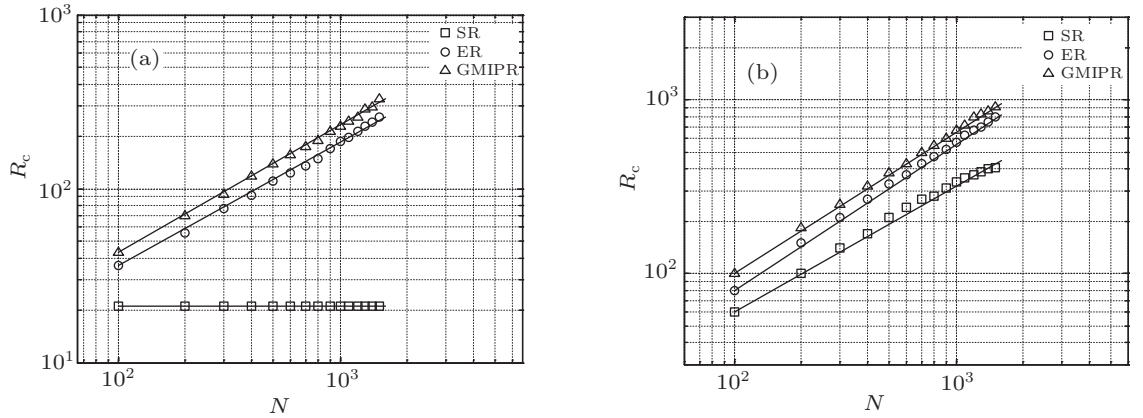


Fig. 4. The critical generating rate $R_{\rm c}$ versus the network size N under different routing strategies: (a) $C_i = 5$ and (b) $C_i = k_i$.

Furthermore, we will discuss the relationship between the betweenness centrality and the network size. Reference [25] pointed out that $R_{\rm c}$ can be calculated as: $R_{\rm c} = C \times N(N-1)/b_{\rm max}^{\rm SR}$, where $b_{\rm max}^{\rm SR}$ is the largest betweenness centrality in the network under the SR strategy. We define $b_{\rm max}$ as the largest betweenness centrality in the network under a different routing strategy. It is easily understood that $R_{\rm c}$ is inversely related to $b_{\rm max}$, which means that we can improve $R_{\rm c}$ by reducing $b_{\rm max}$. Hence the scaling of $b_{\rm max}$ with network size N can be seen as a measurement of the scalability of a routing strategy: the faster $b_{\rm max}$ grows with N, the less useful the routing strategy is for large networks.[8] Reference [8] also shows that a good routing strategy is required to meet at least two properties: (i) minimize the difference between the maximum and average betweenness centrality, and (ii) do this while keeping the difference between the average betweenness centrality computed by using the routing strategy and the one computed by using the SR strategy as low as possible.

In Fig. 5, the average $b_{\rm max}$ obtained under our

routing strategy is depicted as a function of the network size N. We find a power-law increase with a function form $b_{\max} \sim N^{\alpha}$, and $\alpha_{\rm GMIPR} = 1.2$. In the same figure, comparing with the SR strategy $\alpha_{\rm SR} = 2.1$ and the ER strategy with $\alpha_{\rm ER} = 1.3$, we find that our routing strategy produces an acceptable value of the exponent α. As shown in Table 2, comparing with the average betweenness centrality $b_{\rm avg}$ under the ER strategy, we find that $b_{\rm avg}$ under the GMIPR strategy is smaller, and the difference between $b_{\max}$ and $b_{\rm avg}$ is also smaller than that under the ER strategy. In addition, the difference between $b_{\max}$ and $b_{\rm avg}$ under our routing strategy is only 7.22% of that under the SR strategy, but $b_{\rm avg}$ under our routing strategy is longer than that under the SR routing strategy. This is because the average length of paths under our routing strategy is longer than that under the SR strategy.

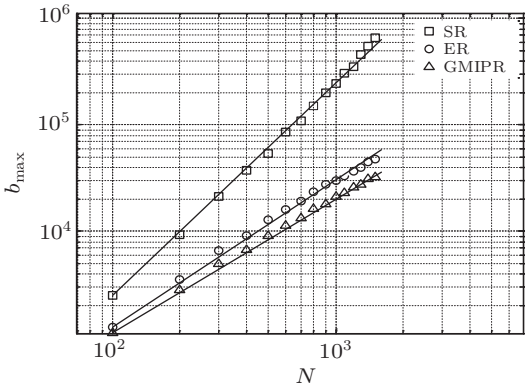


Fig. 5. The maximum betweenness centrality $b_{\max}$ versus the network size N under different routing strategies.

Table 2. The largest betweenness centrality $b_{\max}$ and the average betweenness centrality $b_{\rm avg}$ under the SR strategy, the ER strategy and the GMIPR strategy.

	SR	ER	GMIPR
$b_{\max}$	662066	43400	34617
$b_{\rm avg}$	6322	9758	9176

4. Conclusion

A key element for enhancing network transmission performance is making the traffic load distribution accord with the distribution of node capability for packet delivery. In addition, the average length of the paths in a network should still maintain the small-world property. To this end, we proposed a routing strategy based on the global information of a network structure, named the GMIPR strategy. This routing strategy leads the information packets to be transmitted along the path, on which the logarithmic sum of node degree is at a minimum. Simulation results show that the network using our routing strategy demonstrates better transmission performance than that under the SR strategy and the ER strategy in various distributions of node capability for packet delivery.

When the nodes have the same capability, as shown above, it is obvious that the traffic load under the GMIPR strategy is not distributed evenly to the nodes. Thus our routing strategy can be improved further. In future work, we will take the dynamic information of network and optimal methods into consideration to enhance the network transmission performance further.

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