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The Effect of Queueing Strategy on Network Traffic*

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Abstract *In recent years, the transportation system has been faced by increasing challenge in congestion and inefficiency, and research in traffic network has become a significant area of interest. In this paper, we introduce a dynamic-information-based (DIB) queueing strategy into network traffic model under the efficient routing strategy. DIB makes a packet with higher priority to be delivered if there are less packets travelling along its path from the current node to the destination. It is found that, compared with the traditional first-in-first-out (FIFO) queueing strategy, DIB can effectively balance the traffic load of the system via delaying packets to be delivered to congested nodes. Although the network capacity has no obvious changes, some other indexes which reflect transportation efficiency are efficiently improved in the congestion state. Besides, extensive simulation results and discussions are provided to explain the phenomena. The results may provide novel insights for research on traffic systems.*

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Key words: networked traffic, complex network, queueing strategy, scale-free network

1 Introduction

Ranging from natural systems to social systems, many complex systems can be abstracted into networks. Individuals in these systems can be represented by nodes and connections among individuals who can be represented by edges.[1−5] Originally, regular network and random network are used to denote the structure of real systems. Apparently, they cannot factually reflect the characteristics of the real systems. Researches on complex networks have become prevailing after small-world phenomenon[6] and scale-free property[7] were discovered at the end of the 20th century.[8−14] Especially, network traffic has attracted much more attention in the past decade as many networked systems (such as air traffic system,[15] Internet and World Wide Web[16−17]) play an important role in modern society and the congestion becomes more and more serious. For instance, in China, the air traffic congestion caused hundred millions of dollars' losses and the Internet congestion caused more than 5 billion of dollars' losses in year 2011.

Network traffic models are proposed to mimic the traffic process, and the traffic system is abstracted into network primarily. At each time step, packets are produced, whose sources and destinations are chosen randomly, and they can travel based on some routing protocols.[18−21] The network capacity is defined by a critical packet generating rate, above which the system will reach congested state from free-flow state.[22]

Previous works on network traffic mainly focus on routing strategies.[23−24] The random walk strategy has been researched at the very beginning.[25] However, the real traffic behaviour is not random but rather determined. The shortest path strategy is widely adopted in literatures and real life,[26] but it can easily cause the overload of hubs. Yan *et al.* proposed an efficient routing strategy via redistributing traffic loads from central nodes to noncentral nodes, which can improve the network capacity more than ten times.[27] Both shortest path strategy and efficient routing strategy need the knowledge of the whole system, which will become impractical if the network size is huge. Consequently, routing strategies using local topological information have been studied. With consideration of local topological information, Wang *et al.* presented the nearest neighbor searching strategy.[28−29]

Optimizing the underlying network topology is also an important topic. Adding or removing a few links in the existing network becomes the common method. Some strategies have been proposed to improve the network capacity effectively. In heterogeneous networks, hub nodes usually endure more traffic load, causing links between them much more easily to get jammed. Liu *et al.* proposed a high-degree-first (HDF) link removal strategy to remove

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the congested links, which can lead to the redistribution of traffic load so as to enhance the network capacity.[30] Zhang *et al.* proposed a high-betweenness-first (HBF) link removal strategy, which can also enhance the network capacity. Both HDF and HBF strategies are far from "optimal".[31] Huang *et al.* proposed a novel variance-of-neighbor-degree-reduction (VNDR) link removal strategy via introducing the simulated annealing (SA) algorithm into network traffic.[32] The VNDR strategy outperforms the HDF strategy and the HDF strategy, because it not only considers the role of hub nodes, but also balances the traffic load from each node to its neighbors.

Moreover, network traffic dynamics also has broader applications in studying other kinds of dynamics, such as epidemic spreading.[33−34] Meloni *et al.* adopted a different perspective and showed that the epidemic incidence is shaped by traffic-flow conditions. In the scenarios in which the delivery capability of the nodes is bounded or unbounded, the threshold values depend on the traffic and decrease as flow increases.[33] Wang *et al.* found that intraspecies infection can strongly promote coexistence while interspecies spreading can not.[34] These results were quantified and a theoretical paradigm based on nonlinear partial differential equations was derived to explain the numerical results.

In network traffic models, the delivering capability of nodes is finite in general. The packet queue length in the buffers of some nodes will exceed their delivering capability with the continual increase of packets rushing into the system. Therefore, how to choose the packets to be delivered becomes a critical problem. To our knowledge, in previous works, usually the first-in-first-out (FIFO) protocol is adopted. However, the FIFO strategy is not the optimal.[35]

Especially, people find that the consideration of dynamic information can effectively improve network performance. Wang *et al.* presented a routing strategy integrating local static and dynamic information, which can enhance the network capacity and the communication velocity compared with the strategy based on local static information.[29] Ling *et al.* introduced a global dynamic routing strategy for the networks and it is found that the system capacity is almost two times as much as that with the efficient routing strategy.[36] Therefore, in this paper, we introduce a dynamic-information-based (DIB) queueing strategy into network traffic model. The DIB strategy makes a packet with higher priority to be delivered if there are less packets waiting in its path from current node to destination. It is found that, compared with traditional FIFO strategy, the network capacity has no obvious changes, but some other transportation indexes can be efficiently improved by the DIB strategy.

The paper is organized as follows. In the next section, the network traffic model is introduced. The simulation results and discussions are given in Sec. 3. The paper is concluded by the last section.

2 The Model

Since many previous works have testified that realistic networks (such as Internet and World Wide Web, and airline routes[1,3−4]) are usually connected with scale-free and small-world properties, in this paper we adopt the well-known Barabási–Albert (BA) scale-free network model[7] as the physical infrastructure on which the traffic process takes place.

In network traffic models, at each time step, there are R packets generated with sources and destinations being chosen randomly. The packets are delivered according to a certain routing strategy. Here we adopt the efficient routing strategy proposed by Yan *et al.*[27] For any path between nodes s and d as $\mathrm{Path}(s \to d) : = s \equiv l_1, \ldots, l_i, \ldots, l_{n-1}, l_n \equiv d$, the efficient path between s and d corresponds to the path that makes the value minimum for a given β, which is defined by

$$L(\mathrm{Path}(s \to d) : \beta) = \sum_{i=1}^{n} k(l_i)^{\beta} \,, \tag{1}$$

where k is the degree of a node and β is a tunable parameter. In the network traffic, each node has two functions: delivery and storage packets. The delivery capability of each node is denoted by C. The packet queue length in the buffers can be infinite. Assuming that L_i^t is the number of packets queueing in the buffer of node i at time step t, then the number of packets p_i^t which will be delivered can be denoted as

$$p_i^t = \begin{cases} L_i^t \,, & \text{if } L_i^t < C \,, \\ C \,, & \text{else} \,. \end{cases} \tag{2}$$

If the queue length is less than C, then all packets can be delivered. Otherwise, C packets are delivered according to a certain queueing strategy and $L_i^t - C$ packets will be delayed.

Then the queueing strategies are described as follows:
(i) The FIFO strategy: p_i^t packets are delivered following the first-in-first-out protocal.
(ii) The DIB strategy: For a packet u queueing in the buffer of node i at time t, S_u^i indicates the number of packets which are travelling on the surplus path of the packet u: $S_u^i = \sum_{n \in P_u} L_n$, where P_u is the path of packet u from node i to its destination, and L_n is the numer of packets at node n. p_i^t packets with minimum S^i are selected from L_i^t queueing packets to be delivered to their next nodes.

The whole traffic process consists of following steps:
(i) Parameter configuration. We set the network parameters as $N = 1225$ and $m = m_0 = 2$. The queue buffer on each node is unlimited, and the total simulation time T is set as 10 000.
(ii) Packets generation. There are R packets, whose sources and destinations are randomly assigned, generated in the system.
(iii) Packets navigation. Here we adopt the efficient routing strategy.[27]

(iv) Packets delivery. Each node can deliver at most C packets towards their destinations in one time step. And here, the FIFO strategy and the DIB strategy are adopted.
(v) Packets removing. Once packets reach their destination, they will be removed from the system.
(vi) Repeat step (ii) to step (v) for T times.
(vii) Data statistics. Compute these parameters, network capacity, degree of congestion, communication velocity, average packets traveling time, average packets waiting time, system throughput and traffic load etc., and the details will be described in the next section.

3 Simulation Results and Discussion

We analyze the taffic behavior under these queueing strategies. To be accurate, the simulation results are averaged by 30 individual runs on 30 BA networks with the same network parameters.

Firstly, the order parameter in Ref. [22]

$$\eta(R) = \lim_{t\to\infty} \frac{C}{R}\frac{\langle \Delta N_p\rangle}{\Delta t} \tag{3}$$

is introduced to describe the transitions of traffic flow in the network. In Eq. (3) $\Delta N_p = N_p(t+\Delta t) - N_p(t)$, $\langle\cdots\rangle$ indicates the average over time windows of width Δt, and $N_p(t)$ denotes the number of packets in the network at time t. The capacity of networks is defined by a critical value R_c, at which a continuous transition occurs from free flow to congestion. When $R < R_c$, $\langle\Delta N_p\rangle = 0$ and $\eta(R) = 0$, it indicates that the network is in the free flow state. While for $R > R_c$, $\eta(R)$ is larger than zero, and the system will collapse ultimately. Simulation result of the critical packet generating rate R_c is firstly examined. In Fig. 1(a), the results of the two queueing strategies are shown by different symbols. In order to testify the proposed queueing strategy's robustness, C with different values is also considered. One can find that as β changes from 0 to 2, the values of R_c under the two queueing strategies are almost the same, and they all reach the biggest value at $\beta = 1$. Therefore it can be concluded that the DIB queueing strategy does not affect the value of R_c, namely the network capacity has no significant changes. Previous studies show that the network capacity can be approximately expressed by $R_c = C(N-1)/B_{\max}$, where $B_{\max}$ is the maximal effective betweenness of the network.[20] In our model, C is a constant value, N is 1225, and $B_{\max}$ is determined by the efficient routing strategy. Therefore Rc remains unchanged. However, one can find that in Fig. 1(b), the values of the order parameter $\eta(R)$ under the queueing strategies behave differently. The trend of the results under the two queueing strategies is quite alike: for all values of beta $\eta \approx 0$ when R is small, while it dramatically increases when R is larger than R_c. Moreover, one can find that there is almost no difference between $\eta(R)$ of the two queueing strategies in free-flow state. In the free-flow state, the load of most nodes is small, and packets do not need to queue, thus the queueing strategy does not work. However, in the congestion state, one can find that $\eta(R)$ of the DIB strategy is smaller than that of the FIFO strategy. Next we will analyze the difference between the two queueing strategies in details. For the sake of simplicity, C is set as 1 in the following simulations. We also examine the results of other values, and it is found that the main conclusion is alike.

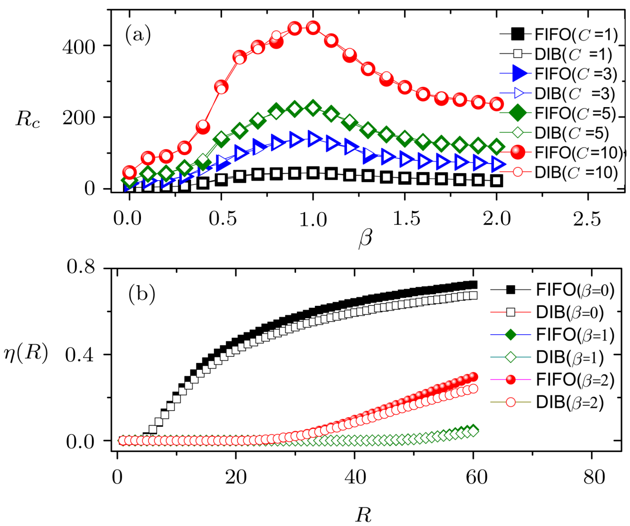

Fig. 1 (Color online) (a) The relationship between network capacity R_c and β with $C = 1$, 3, 5, and 10. (b) The relationship between the order parameter $\eta(R)$ and the packet generating rate R under the queueing strategy when β is set as 0, 1, and 2. Here $N = 1225$, $T = 10\,000$, and $C = 1$.

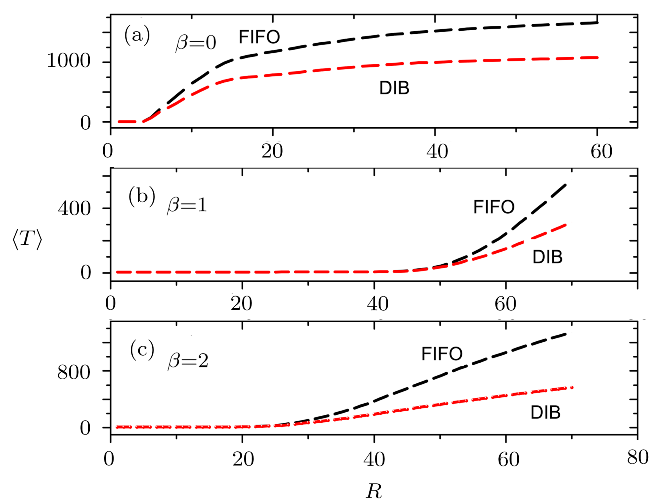

Fig. 2 (Color online) The relationship between the average traveling time $\langle T\rangle$ and the packet generating rate R under the FIFO and DIB queueing strategies when β is set to 0 (a), 1(b), and 2(c). Here $N = 1225$, $T = 10\,000$, and $C = 1$.

The average travelling time $\langle T\rangle$ is a critical feature for traffic systems, which reflects the traffic velocity. For example, for the air traffic system, how to reduce the delay cost is an important problem currently, and decreasing the average travelling time of flights is an effective measure. Figure 2 shows the relationship between $\langle T\rangle$ and the packet generating rate R under different β. Here $\langle T\rangle$ can be denoted as

$$\langle T\rangle = \sum_{i=1}^{N_{\rm arrive}} t_i \Big/ N_{\rm arrive}\,,$$

where t_i is the travelling time of arrived packet i, and $N_{\rm arrive}$ is the number of arrived packets. Obviously, the smaller $\langle T\rangle$, the faster the traffic velocity. As Fig. 2 shows, in the free-flow state, packets can be freely delivered, and $\langle T\rangle$ under different queueing strategies keeps the same. In the congestion state, $\langle T\rangle$ dramatically increases when $R > R_c$, because packets have to wait in the buffer due to limited delivery capability. Besides, $\langle T\rangle$ is the smallest when $\beta = 1$ under the two strategies. However, one can find that $\langle T\rangle$ of the DIB strategy is always smaller than that of the FIFO strategy in the congestion state. For example, when $R = 70$ and $\beta = 1$, $\langle T\rangle$ in FIFO is 576, but only 314 in DIB.

The ratio of waiting time to travelling time $P_{\rm wt}$ is another critical feature for traffic systems to describe traffic efficiency. It is an important index to depict user satisfaction. The less $P_{\rm wt}$ is, the higher the user satisfaction is. For example, it may be tolerable for a driver to be delayed 10 minutes in his 2 hour travel. However, it is unacceptable to a driver when the travel only takes a very short time. $P_{\rm wt}$ can be denoted as

$$P_{\rm wt} = \Big(\sum_{i=1}^{N_{\rm arrive}} w_i \Big/ t_i\Big) \Big/ N_{\rm arrive}\,, \tag{4}$$

where w_i is the waiting time of packet i, and t_i is its total travel time. In Fig. 3, one can see that with the increment of R, $P_{\rm wt}$ of the queueing strategy increases obviously. Besides, the result is almost the same as the result of $\langle T\rangle$. $P_{\rm wt}$ of the DIB strategy and the FIFO strategy is the smallest when $\beta = 1$. However, one can find that $P_{\rm wt}$ of the DIB strategy is always smaller than that of the FIFO strategy, especially for the congestion state. When $R = 70$ and $\beta = 1$, $P_{\rm wt}$ for the two strategies are 0.77 and 0.44 respectively. Therefore, the DIB strategy outperforms the FIFO strategy again.

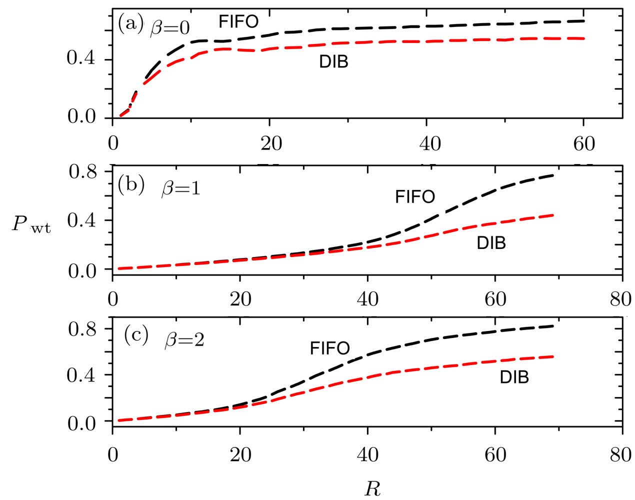

Fig. 3 (Color online) The relationship between the rate of waiting time to travelling time $P_{\rm wt}$ and the packet generating rate R under the queueing strategies when β is set to 0(a), 1(b), and 2(c). Here $N = 1225$, $T = 10\,000$, and $C = 1$.

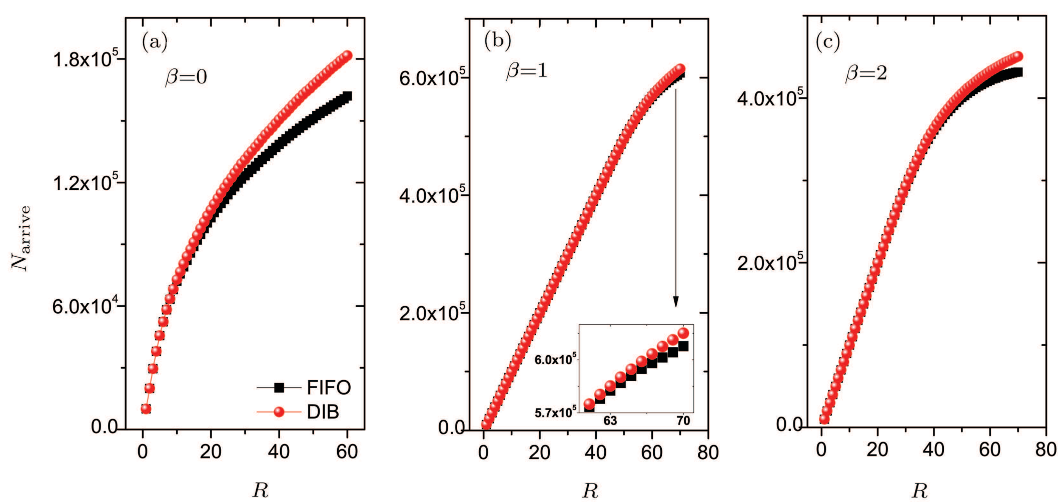

Fig. 4 (Color online) The relationship between the number of arrived packets $N_{\rm arrive}$ and the packet generating rate R under the queueing strategies when β is set to 0(a), 1(b), and 2(c). Here $N = 1225$, $T = 10\,000$, and $C = 1$.

The system throughput $N_{\rm arrive}$ is the index denoting the total number of packets delivered to their terminals in a fixed time span. It indicates the delivery capability of the whole network. Figure 4 shows the relationship between $N_{\rm arrive}$ and the packet generating rate R. In the free-flow state all packets can successfully arrive at their destinations, and $N_{\rm arrive}(R) \approx T \times R$. However, in the congestion state, not all packets can arrive at their destinations and thus $N_{\text{arrive}}(R) < T \times R$. One can see that N_{arrive} of the DIB strategy and the FIFO strategy are the smallest when $\beta = 1$, and5N_{arrive} of the FIFO strategy is always smaller than that of the DIB strategy.

The system utilization rate (SUR) is the utilization rate of nodes' delivering capability in the system. It can be denoted as

$$\text{SUR} = \frac{\sum_{t=t_0}^{T} N_{\text{deliver}}(t)}{N \cdot (T - t_0)}\,, \tag{5}$$

where $N_{\text{deliver}}(t)$ is the number of nodes which deliver packets at time t, and t_0 represents a fix time when the system is in steady state (here $t_0 = 9000$). Obviously, too low SUR will result in waste of valuable system resources. Figure 5(a) shows the relationship between SUR and β under the two strategies. In efficient routing strategy the average length of packets' paths increases with the increment of β,[27] therefore more nodes are involved in packets delivery. We can see that with the increase of β, the value of SUR under different strategies monotonously increases. What is more, SUR of the DIB strategy is larger than that of the FIFO strategy in congestion state. In order to better explain the underlying mechanism, we investigate the distribution of the utilization frequency of nodes (UFN) with different degree in congestion state when β is 0, 1, and 2 (Figs. 5(b)–(d)). UFN of nodes with degree i is denoted as

$$\text{UFN}_i = \frac{\sum_{t=t_0}^{T} N^i_{\text{deliver}}(t)}{N_i \cdot (T - t_0)}\,, \tag{6}$$

where N_i is the number of nodes whose degree is i, and $N^i_{\text{deliver}}(t)$ is the number of nodes with degree i which deliver packets at time t. UFN_i in large value indicate the nodes with degree i are very busy. On the contrary, UFN_i in small value means these nodes are free. We investigate the distribution of the utilization frequency of nodes (UFN) with different degree in congestion state when β is 0, 1, and 2 (Figs. 5(b)–(d)). One can find that when $R = 80$, the bigger β is, the smaller the degree of busy nodes which have large UFN is. It can be seen that the value of UFN under the DIB strategy is much larger than that of the FIFO strategy when the value of UFN under the two strategies is from 0.1 to 0.9, and the value of UFN_i has no obvious difference under the FIFO and DIB strategies when it is close to 0 or 1. In addition, we can conclude that the DIB strategy can effectively balance traffic load among nodes with different degree, which can improve the utilization frequency of nodes with specific degree. The utilization frequency of nodes with different degree is a precious resource, the improvement of which in many cases may improve the SUR.

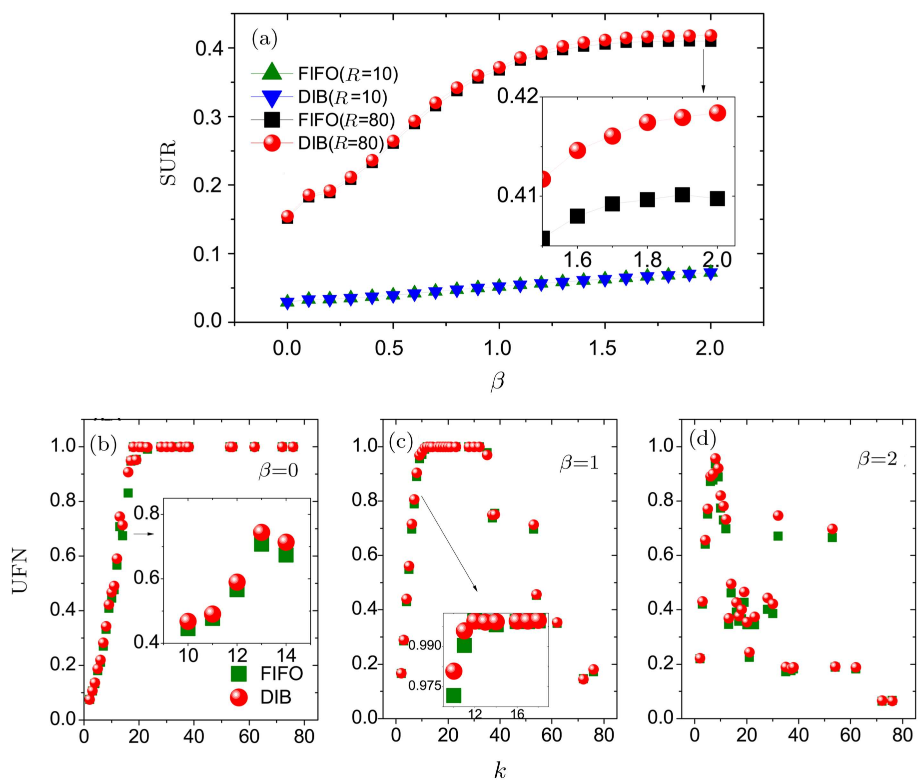

Fig. 5 (Color online) (a) The relationship between SUR and β under the two queueing strategies when $R = 10$ and 80 at the situation of $C = 1$. (b)–(d) The relationship between UFN and the degree of nodes when β is set to 0(b), 1(c), and 2(d) at the situation of $R = 80$ and $C = 1$.

From discussions above, one can find that some indexes reflecting transportation efficiency can be improved in the congestion state under the DIB strategy. In the network traffic model, nodes with larger connections are more likely to bear traffic congestion. So DIB, selecting the packets with minimum number of packets travelling along their paths to be delivered, can balance the load between congested nodes and uncongested nodes. Under the DIB strategy, the traffic flow volume passing through each node does not change, but the packets are delayed to be delivered to congested nodes. Figure 6 further demonstrates our conclusion by comparing the load distribution $n(k)$ under the queueing strategies with $\beta = 0$, 1, and 2. One can find that in the congestion state, the larger β, the smaller the degree of nodes which bear heavy traffic load. Moreover, when $\beta = 0$ the nodes with degree from 30 to 80 are congested. When $\beta = 1$ and 2. the degree of congested nodes are from 10 to 30 and from 3 to 10 respectively. Besides, the load of busy nodes under the DIB strategy is much lighter than that under the FIFO strategy. On the contrary, at the uncongsted nodes, the load under the DIB strategy is slightly heavier than that under the FIFO strategy. It can be concluded that DIB can effectively balance the load between the congested nodes and the uncongested nodes via delaying packets to crowded nodes. Therefore, the system behavior ($\langle T\rangle$, $P_{\rm wt}$, and $N_{\rm arrive}$) can be improved.

In the previous discussions, C is a constant value. However, in many situations C is related to the degree of nodes k.[38–39] Next we consider when $C = k$ and verify the robustness of the strategy DIB. Figure 7 shows the results of the order parameter, average packets traveling time, average packets waiting time, and system throughput under the two strategies. One can see that DIB outperforms FIFO in all aspects.

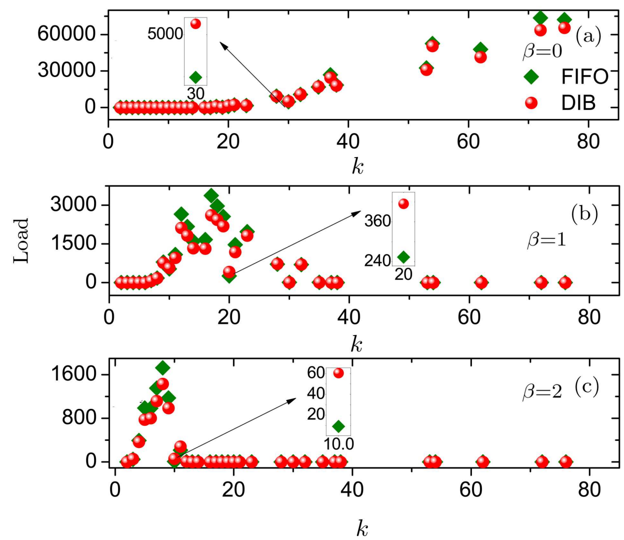

Fig. 6 (Color online) The load distribution in the congestion state under the queueing strategies when β is set to 0(a), 1(b), and 2(c). R =60 for (a), and R =70 for (b), (c).

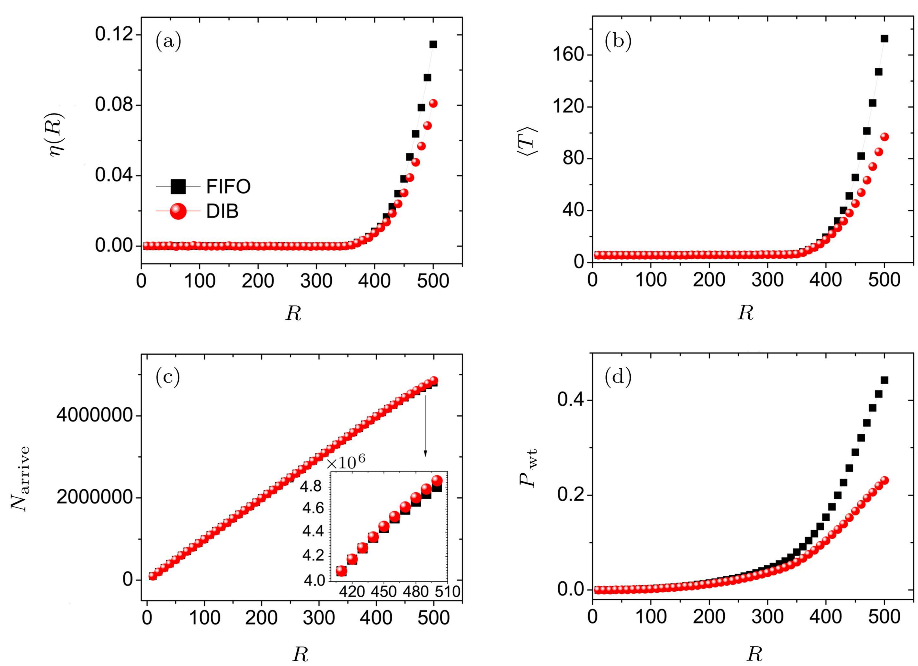

Fig. 7 (Color online) The relationship between $\eta(R)$ (a), $\langle T\rangle$ (b), $N_{\rm arrive}$ (c), $P_{\rm wt}$ (d) and R under the FIFO and DIB queueing strategy when $C = k$. Here $N = 1225$ and $T = 10\,000$.

4 Conclusion

In this paper, we introduce a dynamic-information-based queueing strategy into network traffic model under the efficient routing strategy. The DIB strategy makes a packet with higher priority to be delivered if there is less total number of packets travelling along its path from the current node to its destination. Though DIB does not change packets' paths, it can effectively balance the load by delaying packets to be delivered to congested nodes. Therefore it can mitigate traffic congestion of the crowded nodes and improve the utilization frequency of the deserted nodes. It is found that the DIB efficiently improve some other indexes reflecting transportation efficiency, such as the average travelling time, the rate of waiting time to travelling time and so on. Our work may provide novel insights for research on networked traffic systems.[40]

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