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Effective usage of shortest paths promotes transportation efficiency on scale-free networks

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HIGHLIGHTS

- An efficient queuing strategy in a network traffic model is proposed.
- The traffic efficiency is remarkably improved in the congestion state.
- Our work may be helpful in designing optimal networked-transportation systems.

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ABSTRACT

With rapid economic and social development, the problem of traffic congestion is getting more and more serious. Accordingly, network traffic models have attracted extensive attention. In this paper, we introduce a shortest-remaining-path-first queuing strategy into a network traffic model on Barabási–Albert scale-free networks under efficient routing protocol, where one packet's delivery priority is related to its current distance to the destination. Compared with the traditional first-in-first-out queuing strategy, although the network capacity has no evident changes, some other indexes reflecting transportation efficiency are significantly improved in the congestion state. Extensive simulation results and discussions are carried out to explain the phenomena. Our work may be helpful for the designing of optimal networked-traffic systems.

1. Introduction

Since a wide range of natural and social systems can be represented as networks in which entities are connected by physical or abstract links, there has been a quickly increasing interest in the field of network theory and its applications [1–5]. In early times, simple regular networks, where the number of neighbours is the same for all nodes, were widely explored. In the 1960's, Erdös and Rényi proposed the famous ER random network model, which has dominated this field for almost half a century [6]. Since the renewed attention of small-world phenomenon by Watts and Strogatz [7] and the scale-free property by Barabási and Albert [8] at the end of the last century, people came to realize that a large number of real networks are not simply regular or completely random, but actually display very "complex" properties. Consequently, researches on complex networks have been flourishing in the past decade, e.g., network modelling [9–11], network synchronization [12–14], epidemic spreading [15–18], network controllability [19–21], evolutionary games [22–25], cascading failures [26–29] and traffic dynamics [30–32], have attracted wide attention from different communities. Especially, as the traffic congestion in communication systems, urban traffic systems and air transportation systems is getting more and more severe, network traffic has become a hotspot in recent years [33–41].

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The goal of network traffic study is to alleviate traffic congestion and to improve the transportation efficiency of networked traffic systems. In the commonly used network traffic model, the structure of the transportation system is denoted by a network, while the traffic entities (such as pedestrians, automobiles, aircraft or information flow) is denoted by moving packets whose sources and destinations are randomly selected. As the packet-generating rate R increases, the system will undergo a transition from a free-flow state to a congestion state at a critical packet generating rate R_c, which is also a measure of network capacity. Previous works can be classified into two types: (i) optimizing the underlying network topology; (ii) designing a better routing protocol. In a comprehensive survey by Chen et al. [33], the former is also called "hard" strategy and the latter is called "soft" strategy.

As to the "hard" strategy, the common method is to adding or removing a few links in the existing network, according to some principles to improve the network throughput. Liu et al. proposed a high-degree-first (HDF) link removal strategy, where all links are sorted by $k_i * k_j$ (k_i and k_j are the degree of links' end-nodes) and then closed in descending order [42]. It is found that the network capacity is remarkably enhanced. In heterogeneous networks, hub nodes usually bear more traffic load, resulting in that links between them are much more easily to get jammed. Removing the congested links can lead to the redistribution of traffic load so as to enhance the network capacity. Zhang et al. proposed a high-betweenness-first (HBF) link removal strategy, where the evaluation criterion is weighed as $B_i * B_j$ (B_i and B_j are the betweenness of the two nodes forming the link), and the network capacity is also enhanced [43]. Both high-degree-first strategy and high-betweenness-first strategy are guiding rules for structure design, but they are far from "optimal". Huang et al. introduced the simulated annealing (SA) algorithm into network traffic and proposed a novel variance-of-neighbour-degree-reduction (VNDR) link removal strategy. The variance-of-neighbour-degree-reduction strategy not only considers the role of hub nodes, but also balances the traffic load from each node to its neighbours, and thus it outperforms high-degree-first strategy and high-betweenness-first strategy [44]. Huang et al. also investigated how to add links or nodes into an existing network in an efficient way and some interesting results are reported [45].

Compared with a costly "hard" strategy, a "soft" strategy is more economical and more flexible, and it draws more interest from researchers. The mainstream of "soft" strategy is developing a routing strategy. The random walk has been extensively studied, due to its wide applications [46,47], but it is too simple to reflect a real traffic process. The shortest path routing protocol is widely adopted in transportation or communication systems due to its low economical and technical cost [48–51]. However, if all packets follow the topological shortest path between the sources and destinations, the heavily linked hub nodes are easily congested. In an improved efficient routing protocol by Yan et al., the hub nodes are moderately bypassed. Since the traffic loads of those central and noncentral nodes are well balanced, the network capacity is improved more than ten times [30]. Ling et al. proposed a global dynamic routing strategy, where packets are transported following the path in which the sum of the traffic load of nodes is minimal [52]. Since the traffic load is more accurate than the static topology information, the global dynamic routing strategy performs better than the efficient routing with no surprise. The routing strategies above are based on global information, which is impractical for a huge system. To overcome this challenge, Wang et al. proposed a nearest neighbour searching strategy based on local topological information [31]. Furthermore, it is found that integrating dynamic information into routing protocol can enhance the network capacity [53,54]. Besides, many other mechanisms in network traffic model, such as limited buffer [55], bandwidth allocation [56], packet-delivering capacity allocation [57,58], mobility effect [59] and limited life cycle [60,61], etc., have been extensively explored in the past few years.

In most existing works, if the queuing length is larger than one node's delivering capacity, the common first-in-first-out (FIFO) queuing strategy is adopted to deliver packets waiting in the buffer of each node. Obviously, the FIFO strategy is simple and convenient, but far from optimal. Very recently, Kim et al. introduced the packet priority into network traffic model and studied the jamming transition where packets are discharged according a pre-set priority [62]. They found that the traffic behaviour of the system is improved in the congestion region but worsened in the free flow region. Inspired by their work, we proposed a shortest-remaining-path-first (SRPF) queuing strategy in which a packet's priority is determined by the distance between its current location and destination. It is found that, although the network capacity has no evident changes, the transportation efficiency is greatly improved, especially in the congestion state.

The paper is organized as follows. In the next section, we describe the model of network traffic and the shortest-remaining-path-first queuing strategy used in this work. The simulation results and discussions are given in Section 3. The paper is concluded in the last section.

2. The model

Since many realistic traffic networks are associated with scale-free and small-world properties [63–66], the well-known Barabási–Albert (BA) scale-free network model is usually used to represent the physical infrastructure of traffic systems. The BA model can be constructed by two rules named "growth" and "preferential attachment" [8]. Starting from a fully connected graph with m_0 nodes, one node with m links is added at every time step according to the preferential attachment rule, where the probability of connecting to an existing node i is proportional to the degree. After $N - m_0$ time steps, a network with N nodes whose degree distribution is $p(k) \sim k^{-3}$ is generated. Following common practices, all nodes in the network are able to deliver and store packets [30,31].

The whole traffic process consists of the following steps:

(1) *Parameters setting.* We set the network parameters as $N = 1225$ and $m = m_0 = 2$. The delivery capability of each node is $C = 1$ and the queue buffer of each node is unlimited. The total simulation time is $T = 10{,}000$.