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Effects of Network Topologies on Performance of Communication Networks

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Abstract—We consider packet-based communication networks using minimum distance routing strategy, and compare the traffic performance of different types of networks, namely, scalefree and random networks, in terms of drop probability and transmission delay. Moreover, we show that contrary to intuition, the minimum-distance routing strategy can lead to sub-optimal information transmission performance.

1. Introduction

The advent of digital networked technologies in the past two decades has greatly facilitated the generation, transmission, processing and sharing of information among people in different parts of the world. The resulting highly connected community has played an important role in enhancing efficiency of many operations in commerce, business, government, education, and public services. The reliable and efficient transmission of information is pivotal to the healthy growth of our networked communities. The way in which people (or information sources and destinations) are connected can be described by a *network*, and the network structure determines how efficient information can be shared and transmitted within the network. In our study here, we distinguish the structure of a network in terms of the statistical distribution of the degrees of the nodes in the network. In particular, we will focus on *scalefree* networks and *random* networks in this paper.

Digital transmission has proven to be an effective mode of communication, and one common way of transmitting digital information is to send "packets" from sources to destinations via specific routes in the network [1]. Thus, the routing method also affects the transmission performance. In this paper, we study the effects of network structure on the performance of packet-based communication, and in particular we will compare the scalefree and random networks in terms of some selected performance parameters, such as packet drop probability and transmission time. We show that when a minimum-distance routing algorithm is adopted, the scalefree networks and random networks show relative advantages under different conditions. Further, contrary to intuition, minimum-distance routing does not necessarily lead to optimal performance and increased traffic congestion can be resulted under certain conditions.

In Section 2, we explain the operation of packet-based communication in typical networks, and describe the two types of networks under study, namely *scalefree* networks and *random* networks. In Section 3, we present the performance comparison of the two network types in terms of packet drop probability and transmission delay time, under the minimum-distance routing algorithm. From numerical simulations, we clarify the relative advantages of the two types of networks. Furthermore, we study the effect of minimum-distance routing on the traffic performance and identify the condition under which the minimum-distance routing loses its presumed advantage.

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2. Communication Network Operation

Our main aim in this paper is to study the effects of network structure on the performance of packet-based communication, which is widely used in practice. One typical example is the Internet. In this communication network, *nodes* are routers or computers and a connection is a *link* that joins two nodes together. Data or information is presented as packets and transmitted through connections in the network. In order to analyze the performance of packet-based communication, we need to build an operation model to describe the network data traffic.

2.1. Operation Model of Network Data Traffic

In this network, there are two kinds of nodes: hosts and routers. *Hosts* refer to the nodes that can generate and receive packets, and *routers* can only store and forward packets. The density of hosts ρ is the ratio of the number of hosts to the total number of nodes in the network, and in this paper, we set $\rho = 0.1$. The hosts are randomly distributed in the network. Packets are created by the hosts and sent through the links one step at a time until they reach the destinations. Also, each node in the network has a buffer, the buffer size for node i being $B(i)$. Then, the data traffic operates as follows:

1. Packet Generation: At each time step, new packets are generated by hosts. The average number of generated packets by a host, node i, is λ_i, which is defined as the generation rate of node i. When a packet is generated, its destination is randomly chosen from other hosts. The newly generated packets are put at the end of the buffer of that host.

2. Packet Transmission: The transmission rate for node i per step is δ. At each time step, the first δ pack-

ets of each node are forwarded to their destinations by one step according to the routing algorithm. The routing algorithm adopted here is the simple minimum-distance routing algorithm.

3. Packets Dropped: If the total number of packets reaching one node is larger than its buffer, the outstanding packets are dropped or destroyed.

4. Packets Released: Packets already arrived at their destinations are released from the buffer.

2.2. Network Topology

Performance comparison is made here between two kinds of networks, namely *random* and *scalefree* networks. The random network is a well-known network model proposed by Erdos and Renyi [2], which is constructed as follows. In a network with N nodes, we connect each pair of nodes with a probability p. If N is large enough, the total number of connections in the network is a variable whose mean is $pN(N-1)/2$, and the degrees of the nodes follow a Poisson distribution [3], i.e.,

$$P(k_i) = \frac{\langle k \rangle^{k_i} e^{-\langle k \rangle}}{k_i}, \tag{1}$$

where k_i is the degree of node i, and $\langle k \rangle = p(N-1) = pN$ is the mean value of k_i. Since each pair of nodes are connected with equal probability, the random network is a homogeneous network in which most of the nodes' degrees are around pN. However, recent research has shown that many real-world networks, including many communication networks, are heterogeneous networks with a power law degree distribution [4]:

$$P(k_i) \sim k_i^{-\gamma}, \tag{2}$$

where γ is the characteristic exponent. Such networks are called *scalefree* networks. Equation (2) indicates that in the network, while a small number of nodes have a large number of connections, most other nodes have very few connections. To construct the scalefreee network, we adopt the Barabasi-Albert (BA) growth model here [4]. The algorithm for constructing a BA network is as follows:

1. The starting point is a network of m_0 nodes connecting one another. At each time step, one new node is added to the network and is connected to other m existing nodes, with $m < m_0$.

2. In choosing the nodes to which a new node connects, node i will be selected to connect with the new node with probability $P_i = k_i / \sum k_j$.

After t time steps, the network has $N = t + m_0$ nodes and mt links. Numerical simulations indicate that the degree distribution of the network follows a power law with $\gamma = 3$, i.e., $P(k_i) \sim k_i^{-3}$.

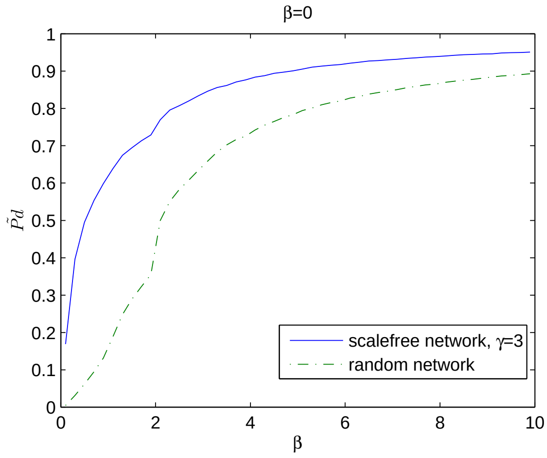


Figure 1: Average packet drop probability $\tilde{P}_d$ versus generation rate λ. Buffer size for node i is $B(i) = 2$.

3. Performance Comparison

Using the network model described above, we build the scalefree and random networks. To compare these two network structures, we consider two communication performance parameters, namely, packet drop probability and transmission time. We define the **packet drop probability** of time step t, denoted by $P_d(t)$, as

$$P_d(t) = \frac{\text{number of dropped packets in time step } t}{\text{number of generated packets in time step } t}, \tag{3}$$

The **transmission time** for packet i, denoted by $T(i)$, is defined as the number of time steps it takes to arrive at the destination from the source.

In this model, larger drop probability or longer transmission time means higher congestion level in the network.

The simulation parameters are set as follows. The number of nodes $N = 1000$, the mean value of node degree $\langle k \rangle = 7.9$, the transmission rate per time step $\delta = 2$, and the buffer size for each node is given by

$$B(i) = \mu \times k_i^{\beta} \tag{4}$$

where μ is set as 2. Thus, for $\beta = 0$, the buffer size is 2 for all nodes, and for $\beta > 0$, the nodes with higher degrees have larger buffers. Furthermore, all the hosts in the network have the same packet generation rates λ, which is varying from 0 to 10.

In our simulation, we observe that the networks reach steady state after about 200 time steps. Thus, it suffices to take the average packet drop probability between 1000 to 1500 time steps as the average steady-state drop probability, i.e.,

$$\tilde{P}_d = \frac{1}{500} \sum_{t=1001}^{1500} P_d(t) \tag{5}$$

where $\tilde{P}_d$ is defined as the average packet drop probability.

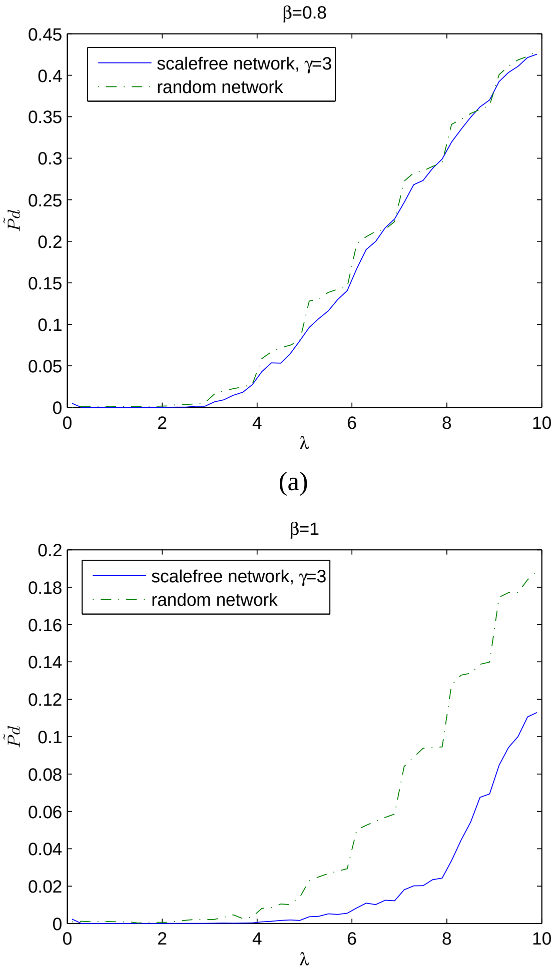


Figure 2: Average packet drop probability $\tilde{P}_d$ versus generation rate λ. Buffer size for node i is $B(i) = 2\,(k_i)^{\beta}$, where $(a)\ \beta = 0.8$, $(b)\ \beta = 1$.

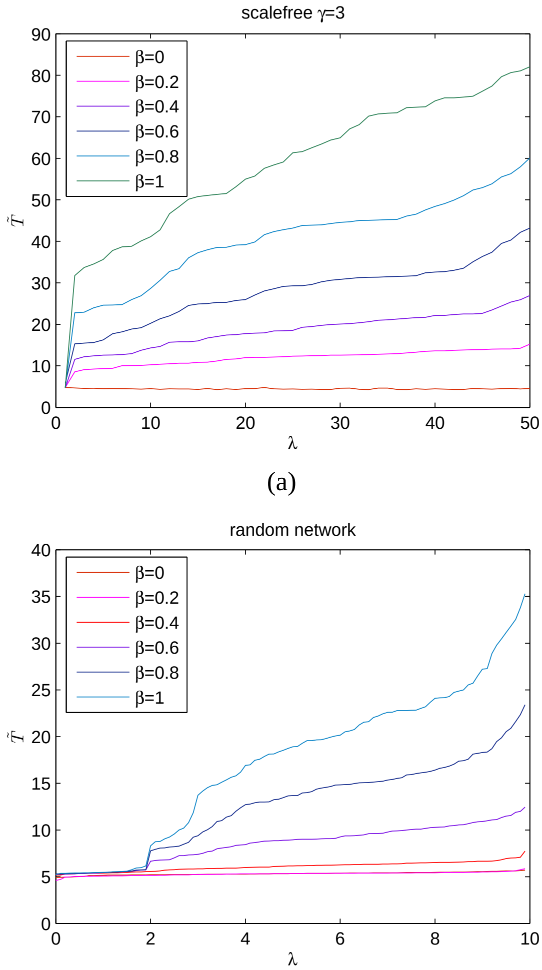


Figure 3: Average transmission time $\tilde{T}$ versus generation rate λ, for (a) scalefree network, and (b) random network. Buffer size for node i $B(i) = 2\,(k_i)^{\beta}$, for β from 0 to 1.

For the calculation of average transmission time, we choose 1000 successfully arrived packets after reaching the steady state, and track their status from their generation to arrival. Then, the average transmission time of the arrived packets is given by

$$\tilde{T} = \frac{1}{1000} \sum_{i=1}^{1000} T(i+m), \tag{6}$$

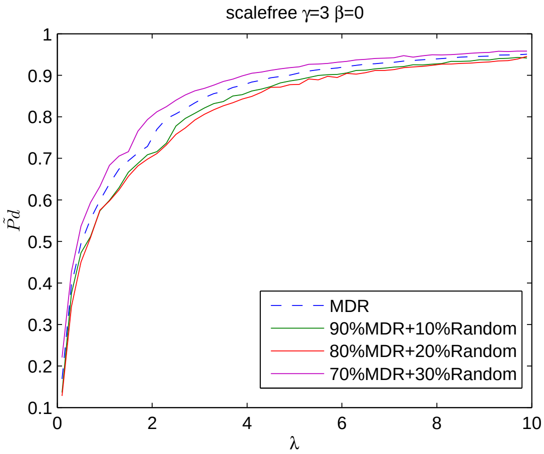
where $T(i+m)$ is the transmission time of the $(i+m)$-th arrived packet, and m is a constant to ensure that the $(i+m)$-th arrived packet is generated in the steady state.

Figure 1 compares the average drop probability $\tilde{P}_d$ versus the generation rate λ in scalefree and random networks, with buffer set to 2 for all nodes, i.e., $\beta = 0$. Here, the random network has a lower average drop probability, especially when the generation rate is relatively low. This result can be reasoned as follows. In the scalefree network, nodes with a higher degree are chosen as routers with a higher probability, and the traffic intensity of them is much higher. Therefore, with all nodes having the same buffer size, the buffers of some high-degree nodes are insufficient, whereas the buffers of most low-degree nodes are rarely used. However, in the random network, due to its homogeneousity, the traffic load is more uniformly distributed for all the nodes.

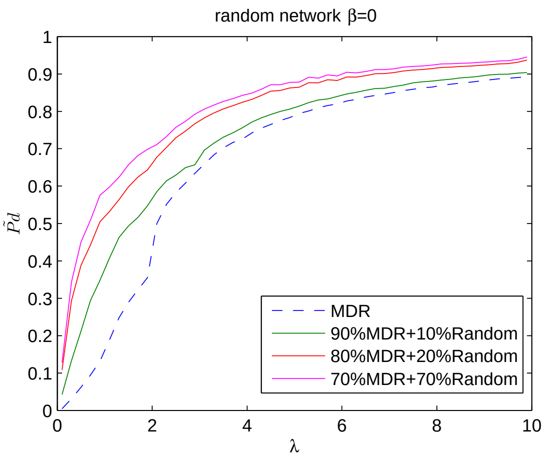
Figure 2 shows that for both scalefree and random networks, as β increases, the average packet drop probability under the same network setting will decrease. When $\beta = 0.8$, the two networks have similar $\tilde{P}_d$, and if $\beta > 0.8$, the scalefree network excel in terms of $\tilde{P}_d$ than the random network, especially under high traffic intensity.

To ensure a fair comparison of the two kinds of networks, the total buffer sizes of scalefree and random networks with the same β should be nearly equal, and this has been confirmed in our simulations.[1] However, we observe that networks with larger buffer sizes for high degree nodes might not have advantages in transmission time. As shown

[1] Buffer size has a cost implication. Thus, networks of equal buffer sizes can be compared more fairly.



(a)



(b)

Figure 4: Average packet drop probability $\tilde{P}_d$ versus generation rate λ, for (a) scalefree network, (b) random network. We compare the performance of the networks using MDR and randomized MDR.

in Fig. 3, performance is poorer as β increases.

In the above simulations, we employ the minimum-distance routing (MDR) algorithm, which should intuitively give optimal performance as packets should take the shortest routes to get to their destinations. However, if we probe further, in the scalefree network, some high degree nodes will be chosen very frequently under the MDR algorithm, causing congestion under high traffic intensity.

It is thus of interest to consider a modified MDR algorithm, where only some percentage of all the generated packages route with minimum distance, while the rest of packages would simply route randomly. From Fig. 4, we see that by adding some randomization to the MDR, the performance for the scalefree network can sometimes be improved. However, for the random network, adding random routing to the original MDR will not make the network perform better in terms of $\tilde{P}_d$.

Therefore, we further explore the effect of the extent of

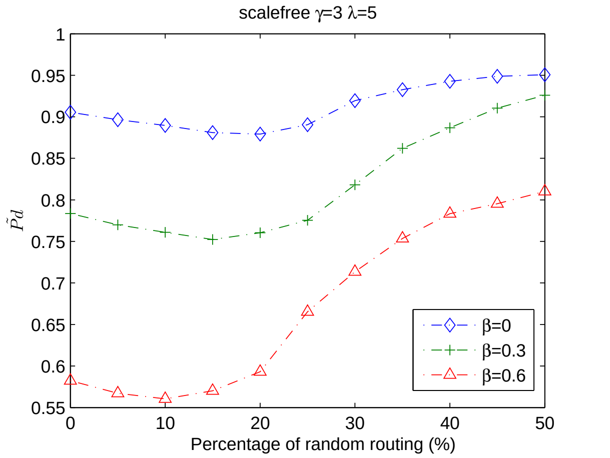


Figure 5: Average packet drop probability $\tilde{P}_d$ versus the percentage of random routing in scalefree network. The average generation rate of hosts λ equals 5.

random routing on the performance of the scalefree network. Fig. 5 shows that, for the scalefree network, $\tilde{P}_d$ will improve with a relatively small amount of random routing. However, as the percentage of random routing continues to increase, $\tilde{P}_d$ will eventually increase and become even worse than that using the original MDR.

4. Conclusions

In this paper, we study the effects of network structure on the performance of packet-based communication, and in particular we compare the scalefree and random networks in terms of packet drop probability and transmission time. We show that when a minimum-distance routing algorithm is adopted, the random network shows advantages in performance when all the nodes in the network have the same buffer sizes. However, if the buffer sizes of scalefree network are power-law distributed, its performance is better than the random network with the same total buffer sizes. Moreover, larger buffer sizes of high-degree nodes will cause longer average transmission time. Finally, we show that contrary to intuition, minimum-distance routing does not necessarily offer optimal performance, especially for the scalefree network.

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