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# Improved routing strategies for data traffic in scale-free networks

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**Abstract.** We study the information packet routing process in scale-free networks by mimicking Internet traffic delivery. We incorporate both the global shortest paths information and local degree information of the network in the dynamic process, via two tunable parameters, $\alpha$ and $\beta$, to guide the packet routing. We measure the performance of the routing method by both the average transit times of packets and the critical packet generation rate (above which packet aggregation occurs in the network). We found that the routing strategies which integrate ingredients of both global and local topological information of the underlying networks perform much better than the traditional shortest path routing protocol taking into account the global topological information only. Moreover, by doing comparative studies with some related works, we found that the performance of our proposed method shows universal efficiency characteristic against the amount of traffic.

**Keywords:** heuristics, network dynamics, random graphs, networks

Complex-network science boomed in the last decade and provides an efficient theoretical framework in which to address problems in a wide variety of fields, ranging from biological and social to technological sciences [1]–[3]. It has been shown that many empirical networks are far from being completely regular or completely random [1], but display non-trivial topological properties, namely small-world and scale-free features [2]. In the light of this, many kinds of dynamical processes, such as epidemic spreading, random walks, synchronization, cascading, and so on, are placed or transplanted on various networks to study the dependence of the dynamical properties on the topological features of the underlying networks [1]–[3].

As one of the hot topics considered in the field of complex networks, information traffic has attracted much attention from the physics community [4]–[17]. In the Internet age, how to improve the efficiency of information packet delivery is becoming one of the most important practical problems [18, 19]. Here, efficiency means minimizing the packet delivery time and/or maximizing the capacity of communication networks. Recently, the packet traffic dynamics in complex networks have been extensively simulated, and it has been shown that the topology of the underlying networks greatly affects the efficiency of the packet traffic on them [5, 6, 10, 11]. When the amount of information is low, a starlike structure was found to be the optimal topology for delivering information [6, 11]. For a large amount of information, however, a starlike topology is very inefficient due to the easily overburdened central node, and the optimal network topology is a homogeneous–isotropic one because of the absence of high betweenness nodes [6, 10].

Since it is inconvenient or even very costly to change the topology of currently existing networks, say, the Internet, it is thus particularly important to develop efficient routing protocols as an alternative way to improve the efficiency of packet delivery [4, 8, 9], [12]–[17]. As was suggested, in heterogeneous networks, the shortest path (SP for short; the paths with minimal number of hops between any source–destination pair) routing strategy easily causes overloading of hub nodes for so many paths going through them [5]. Thus, looking for more efficient routing protocols seems to be very important and necessary. To this end, several alternative routing strategies have been proposed in the past few years, such as the traffic awareness routing strategy [8, 9, 13], efficient path routing [14], the external optimization method [15], and the hub avoidance protocol [16], etc. All these methods have been proved to be superior to the SP routing protocol.

In this paper, we would like to continue the research line of designing better routing strategies for packet traffic. It was argued that the Internet at the autonomous system level shows a scale-free degree distribution [20]. We thus focus here our attention on information packet traffic in scale-free networks. First, we adopt the Barabási–Albert algorithm to build a scale-free network on top of which a packet delivery process is taking place [21]: starting from two nodes, we add new nodes with two links to the existing network one by one; each link of the new node is attached to an existing node $i$ in the network with a probability proportional to its degree $\prod_i = k_i / \sum_j k_j$, where $j$ runs over all existing nodes; during the growth process of the network, duplicate links between nodes are forbidden, and the growth process stops at the time of the network size attaining $N = 5000$. According to [21], the average connectivity and the degree distribution of the generated network are, respectively, $\langle k \rangle = 4$, and $P(k) \sim k^{-\gamma}$ with the exponent $\gamma = 3$ in the large degree limit.

With the underlying infrastructure at hand, we let each node act the roles of a host and a router at the same time. We also let each node possess an infinite queue length, i.e., it can store as many packets as necessary. In order to have a realistic picture of communication, we limit the ability of nodes to deliver packets and assume that, at each time step, each node $i$ can deliver at most $1+k_i^\theta$ packets one step toward their destinations, where $\theta \geq 0$ characterizes the extent of the heterogeneity of the packet-handling ability (in general, it is reasonable to assume that hub nodes have a stronger—or at least equivalent—ability to process packets than the non-hubs; hence $\theta$ is assumed to be non-negative). For convenience, we call $\theta$ the capacity parameter. For $\theta = 0$, all nodes have the same ability irrespective of their link degree, and $\theta > 0$ means larger degree nodes with stronger capacity. At the beginning of the delivering process, each node creates $m_0$ information packets with destinations being randomly selected among the remaining $N-1$ nodes. Thus, the total number of information packets is $N_{\mathrm{p}} = Nm_0$. In subsequent time steps, the packet transmission on the network is implemented by a parallel update algorithm. Each node $i$ processes at most $1+k_i^\theta$ in its queue based on the first-in–first-out rule and selects the next routing nodes for the packets according to the routing strategy given below.

As mentioned above, the SP routing algorithm is not optimal for heterogeneous networks due to the presence of high betweenness nodes. On the other hand, however, the SP routing provides a benchmark for any newly proposed routing protocol. Only those protocols superior to SP routing are of significant and practical importance. To allow a direct comparison with the SP routing, we propose a routing method where the information of the shortest paths among the nodes matters considerably, that is, at each time step, all the packets move from their current position, $i$, to the next node in their path, $j$, with a probability $Q_{ij}$ defined as

$$Q_{ij} = \frac{k_j^\alpha \exp\left[-\beta(d_{it} - d_{jt} - 1)\right]}{\sum_{l\in\Omega_i} k_l^\alpha \exp\left[-\beta(d_{it} - d_{lt} - 1)\right]}, \tag{1}$$

where $\Omega_i$ is the set of neighboring nodes of $i$, $k_j$ is the degree of node $j$, and $d_{it}$ is the minimum number of hops that one starting from $i$ has to pass through in order to reach the target $t$, i.e., the shortest path between $i$ and $t$. The parameter $\alpha$ and $\beta$ are tunable parameters with varying region $\alpha \in (-\infty, \infty)$, $\beta \in [0, \infty)$. For $\alpha = 0.0$ and $\beta \to \infty$, we recover the SP routing strategy. With the decreasing of $\beta$ to zero, the global topological information involved in the routing protocol is reduced. It is worth noting that when $\beta = 0$, we implement exactly a local routing protocol for the packet traffic [12].

The probability $Q_{ij}$ can be called the quality of communication between agents $i$ and $j$ [5]. The essential idea of equation (1) is that we prefer to send packets to a transmitter one step closer to their aims, but when there is more than one alternative, we would like to select a seeming *proper* one according to local topological information (the degree of the candidate nodes). Any finite value of $\beta$ means that the selection of a neighboring transmitter whose distance to the aim is equal to or even greater than that of the present node to the aim is also possible, but with a negligible chance. The rationale behind the form of $Q_{ij}$ is as follows. The heterogeneous abilities of the nodes to deliver information results in heterogeneous amounts of packets waiting in their queues. In order to improve the efficiency, we prefer to send the packets to those nodes with as little waiting time as possible before they are handled. Assume that we have two alternative nodes for sending a packet along its shortest path; one is a hub node (with a stronger ability to handle the task in each time step) and the other a non-hub. If the packet were to wait in the queue of the hub node too long to compensate for the time that it would stay in the queue of the non-hub node, we of course would like to select the non-hub one as the next sender of the packet. In practice, this can be achieved by adjusting the parameter $\alpha$ to help us make an appropriate decision. Positive and negative values of $\alpha$ correspond, respectively, to the preferential selection of a larger degree node and a smaller degree node as the next sender of a packet given that all other aspects of both candidates are the same.

To determine how the above routing strategy influences the efficiency of the information traffic, we implement different realizations of the dynamics for several values of $N_{\mathrm{p}}$ and $\theta$ by varying $\alpha$ and $\beta$ smoothly, and monitor the relevant quantity $\langle T \rangle$, the average time it takes for all $N_{\mathrm{p}}$ packets to travel from their sources to their destinations. To allow a direct comparison with the efficiency of the SP routing, we summarize our simulation results in figure 1, where the relative difference between the average transmit times of our strategies and that for the SP routing, $(\langle T_{\mathrm{sp}} \rangle - \langle T \rangle)/\langle T_{\mathrm{sp}} \rangle$, is shown, varying the values of $\alpha$ and $\beta$ for five combinations of $N_{\mathrm{p}}$ and $\theta$. As can be seen from figure 1, there exist special combinations of $\alpha$ and $\beta$ for the routing algorithm equation (1) to achieve efficient transmission with. It seems that large values of $\beta$ benefit the improvement of the efficiency of the routing strategy irrespective of other parameters, strengthening the important role of the SP information in packet traffic. Nonetheless, it is noted that a traditional SP routing ($\alpha = 0.0$ and a large value limit of $\beta$) performs worse than a routing strategy where the global SP information of the nodes and the local degree information are coupled in an appropriate manner, for example ($\alpha = -2.0$, $\beta = 5.0$). From figure 1, we also note that the performance of our routing strategy shows a strong dependence on the capacity of the nodes (the parameter $\theta$), but less dependence on the total number of packets.

Unlike the case for $\beta$, the choice of $\alpha$ to achieve efficient delivery is mainly influenced by the capacity parameter $\theta$. With increasing $\theta$, the corresponding optimal value of $\alpha$ is also increased (see figure 1). This point is easy to understand. Since larger degree nodes possess more enhanced capacity with increasing $\theta$, it would be better to send the packets to them when facing many alternative choices; hence the increase of $\alpha$. We want to point out that the dependence of $\alpha$ on $\theta$ is quite different when considering local degree information in the packet traffic only. In a recent work [12], Wang and co-workers studied packet traffic dynamics based on a local routing protocol in scale-free networks (our method reduces to their version when $\beta = 0$). They found that when the capacity of the nodes is proportional to their link degree ($\theta = 1.0$), the random walk routing strategy is the best choice, i.e., $\alpha = 0.0$ [12]. In the present case, however, when the global topological information is also involved in the routing strategy, the location of the optimal value of $\alpha$ will be altered (see figure 1 for details). We argue that the presence of the local topological information in the routing strategy can help the packets to circumvent highly jammed nodes (usually those nodes with large degree) and, hence, contribute to the improvement of the performance.

Here we want to remark that, in general, a *good* routing protocol requires that the abilities of handling packets of the nodes (at each time step) should be proportional to their *effective* betweenness, which can be defined as the average number of packages passing through the nodes when every node sends a packet to every other by the use of the routing strategy [10, 14, 15]. For the proposed routing method equation (1), due to

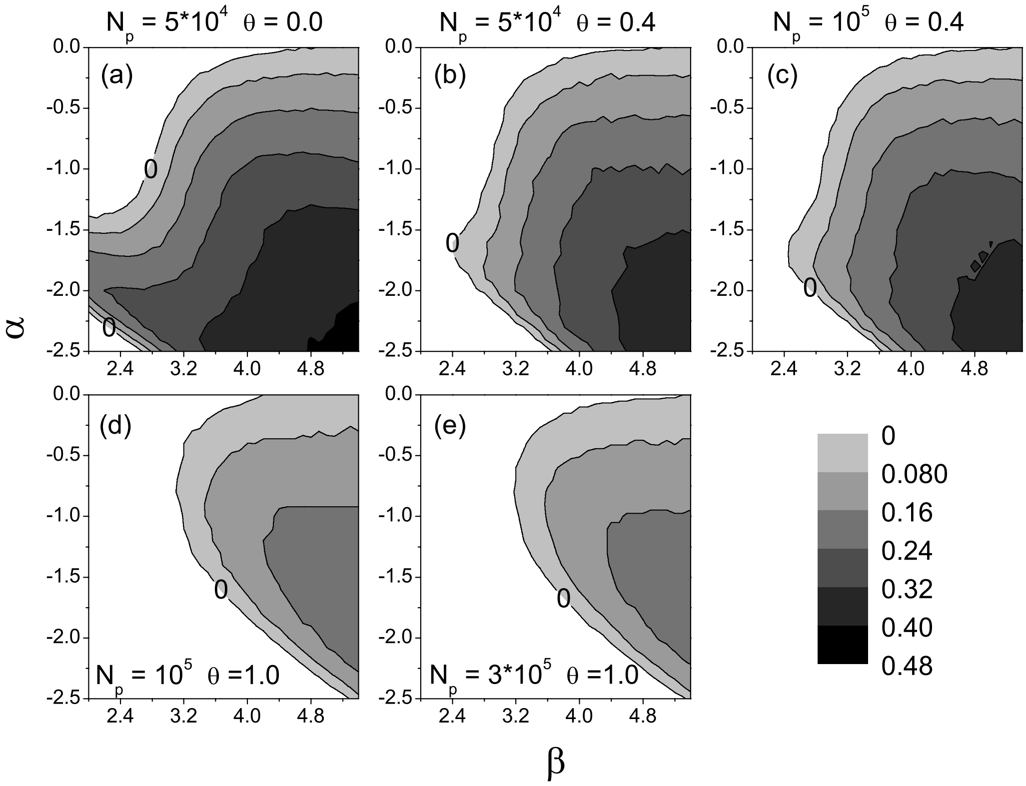


**Figure 1.** The relative difference between the average transmit times of our method and that for the SP routing, $\langle\langle T_{\rm sp}\rangle - \langle T\rangle\rangle/\langle T_{\rm sp}\rangle$, on the $\alpha$–$\beta$ parameter space for several initial numbers of packets $N_{\rm p}$ and capacity parameters $\theta$. From top to bottom and left to right, the parameters $N_{\rm p}$ and $\theta$ are $(5\times10^4, 0.0)$, $(5\times10^4, 0.4)$, $(10^5, 0.4)$, $(10^5, 1.0)$, and $(3\times10^5, 1.0)$, respectively. The results are obtained from an averaging over thirty independent dynamical realizations of information packet transport on several BA scale-free networks. It is obvious that the performance of the routing strategy is independent of the number of packets as long as other related parameters, $\alpha$, $\beta$, and $\theta$, are fixed. Note that only the regions where $\langle T\rangle$ is smaller than $\langle T_{\rm sp}\rangle$ are shown in grayscale. The deeper the color of the region, the more efficient the routing strategy.

the lack of a precise relation for the *effective* betweenness of a node with its degree, it remains an open question how to look for an analytical relationship for the parameters involved, $\alpha$, $\beta$, and $\theta$, in the region of efficient delivery. Nonetheless, it is convenient for us to implement numerical simulations and obtain instructive clues on the setting of the routing parameters (to achieve efficient delivery) as long as we know exactly the structure of a communication network and the abilities of handling packets of the nodes.

In general, the performance of a routing strategy is measured by two indexes: one is the average transmit time of the packets, and the other is the critical packet generation rate $R_{\rm c}$, under which the network is in the free-flow state and beyond which packets accumulate linearly in the network [5, 9, 10, 12, 14, 16, 17]. The value of $R_{\rm c}$ can be estimated by studying the order parameter introduced by Arenas *et al* [5]:

$$\eta = \lim_{t\to\infty} \frac{\langle \Delta N_{\rm p}\rangle}{R\Delta t}, \tag{2}$$

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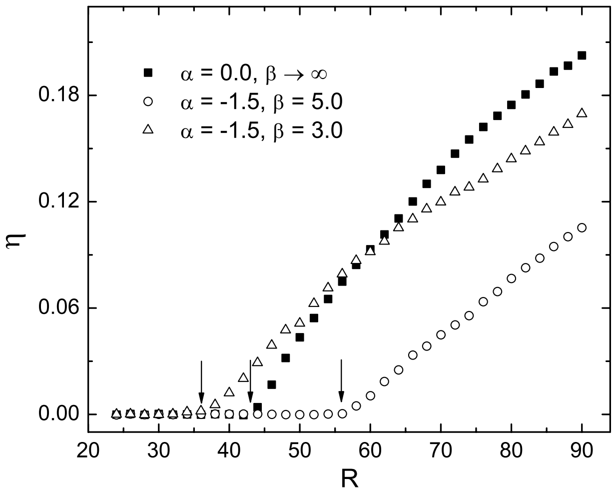


**Figure 2.** The order parameter $\eta$ versus the packet generation rate $R$ for $\theta = 0.4$ and two different combinations of $\alpha$ and $\beta$. The curve for the SP routing is also shown (filled squares) as the basis of comparison. The arrows point to critical values $R_c$ for different routing strategies. Each point is obtained from an average over 10 realizations.

where $R$ is the number of packets created in the network in each time step, $\Delta N_p = N_p(t + \Delta t) - N_p(t)$, $N_p(t)$ is the total number of packets in the network at time $t$, and $\langle \cdots \rangle$ indicates the average over time windows of $\Delta t$. To determine $R_c$, we let the network create $R$ packets in each time step, rather than inserting all packets at the beginning of the dynamics. In figure 2, the order parameter $\eta$ versus the packet generation rate $R$ is shown for $\theta = 0.4$ and two different combinations of $\alpha$ and $\beta$, say, $(-1.5, 3.0)$ and $(-1.5, 5.0)$. For the sake of comparison, the curve for the SP routing is also plotted. It is obvious that the routing strategy $(-1.5, 5.0)$ performs better than the SP routing, as reflected by the increase in the value of $R_c$ and the decrease in the number of accumulating packets at a given packet creation rate $R$. When the global topological information included in the routing strategy is reduced, the performance of the routing strategy deteriorates, as indicated by the lower $R_c$ for the routing strategy $(-1.5, 3.0)$ compared to the other two cases. However, we note that the congestion level for the large $R$ in this case is smaller than that of the SP routing, indicating the efficiency of the routing strategy in heavy traffic.

To enrich our study of the routing algorithm equation (1), we would like to make some comparisons with the work of Echenique *et al* [8, 9]. In [8, 9], Echenique and co-workers proposed a traffic awareness routing protocol, which incorporates local traffic information in packet delivery through a tunable parameter $h$:[1]

$$\prod_i = \frac{e^{-\beta[hd_{it}+(1-h)c_i]}}{\sum e^{-\beta[hd_{jt}+(1-h)c_j]}}, \tag{3}$$

[1] In fact, if we replace $k_i$ in equation (1) by $c_i$ in equation (3), then we also incorporate both dynamical and topological information in the routing algorithm as was done in [8, 9], but with a different coupling formulation. So, we would like to make some comparisons with [8, 9] in this work.

where $\prod_i$ is the probability that a packet is sent through node $i$, $d_{it}$ is the shortest path length between node $i$ and the target, and $c_i$ is the number of packets in the queue of $i$. They showed that under appropriate selection of $h$, the traffic awareness routing strategy can perform much better than the traditional shortest path routing [8]. The mechanism hidden behind this protocol is that it may be more efficient to divert a packet through a larger but less congested path [8, 9].

Looking back at equation (3), we found that this routing rule is sensitive to the total number of tasks assigned to the network. This point can be worked out by analyzing the equation (3): when the value of $c_i$ is very large, i.e., in the case of very heavy traffic, the term $hd_i$ may be negligible as compared to the term $(1 - h)c_i$, since the diameter of most real communication networks grows only logarithmically with system size [20] and any $d_i$ is bounded to the diameter value. Thus the contribution of the term of distance can be ignored in the very heavy traffic case. In other words, this would lead to the loss of shortest path information. When there is no topological information on the destinations of the packets assigned to the routers, it will need a longer time for them to reach the receivers [8]. In fact, it was pointed out by Echenique *et al* in [8] that when the traffic becomes very heavy, the shortest path routing is best suited, and in [9], looking for a dynamically tunable $h$ would strengthen the applicability of the routing algorithm equation (3).

In order to check the above analysis, we have also implemented numerical experiments by the use of the routing strategy equation (3). The simulation results are summarized in figure 3 for different total numbers of packets $N_{\mathrm{p}}$, which are inserted equally in the queues of the nodes at the initial time. The control parameter $\beta$ is set to be 4.0, and each node $i$ can handle at most $1 + k^\theta$ packets with $\theta = 0.4$ in each time step. Figures 3(a) and (b) correspond to $N_{\mathrm{p}} = 10^4$, and $N_{\mathrm{p}} = 10^5$, respectively. It can be seen from the figure that, in the case of a larger number of tasks $N_{\mathrm{p}} = 10^5$, the region of improvement where the performance of the routing protocol is superior to that of the SP routing is greatly shrunk. For comparison, in figure 4 we give the simulation results obtained by implementing our routing algorithm equation (1) with the same parameter setting as in figure 3. Unlike the case for the routing algorithm equation (3), the parameter region of $\alpha$ for which the difference between the average transmit times of our method with that of the SP routing is negative is nearly unchanged. That is to say, the performance of our routing method is insensitive to the amount of traffic flow. We argue that only static topological information is used to guide the packet delivery that contributes to this insensitive behavior.

To summarize, we have studied alternative strategies for traffic delivery in scale-free heterogeneous networks. The proposed method integrates both the global shortest path information and the local degree information for the network in the packet routing process. The performance of the routing protocol is judged by the average transit times of the packets, and also by the critical packet generation rate beyond which packets aggregate continuously in the network. Through numerical simulations we have shown that with appropriate selection of the tunable parameters the routing algorithm presented is superior to the traditional shortest path routing protocol which takes into account the global topological information only. In particular, the improvement of the newly proposed routing strategy benefits two aspects of traffic performance at one time, i.e., minimizing the packet delivery time and maximizing the capacity of the underlying network at the same time. Finally, we want to stress that the performance of the proposed strategy

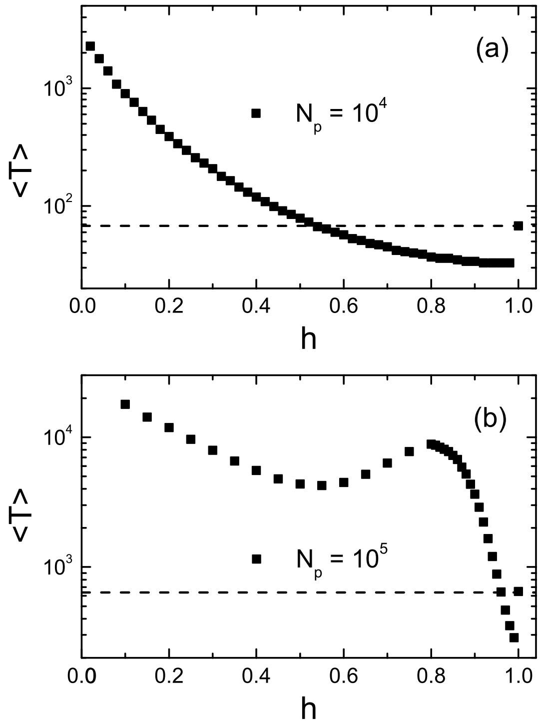


**Figure 3.** The average transmit times of the packets, $\langle T \rangle$, as a function of the tunable parameter $h$ when implementing the routing strategy equation (3). The total numbers of packets inserted initially are $N_{\mathrm{p}} = 10^4$ (a) and $N_{\mathrm{p}} = 10^5$ (b). The average transmit times for the SP routing are also shown (dashed line) as the basis of comparison. Other parameters: $\theta = 0.4$, $\beta = 4.0$.

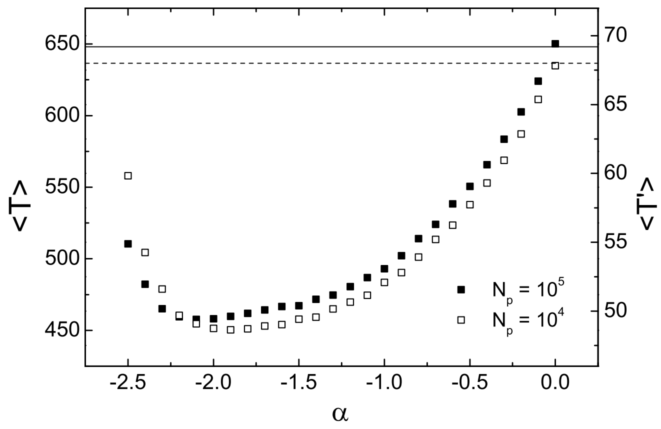


**Figure 4.** The average transmit times of the packets, $\langle T \rangle$, as a function of the capacity parameter $\theta$ when implementing the routing strategy equation (1). The total numbers of packets inserted initially are $N_{\mathrm{p}} = 10^4$ (open symbols) and $N_{\mathrm{p}} = 10^5$ (filled symbols). The average transmit times for the SP routing are also shown by the dashed and solid lines (corresponding to $N_{\mathrm{p}} = 10^4$ and $10^5$, respectively) as the basis of comparison. For convenience, $\langle T' \rangle$ for $N_{\mathrm{p}} = 10^4$. Other parameters: $\theta = 0.4$, $\beta = 4.0$.

shows a universal efficiency characteristic against the amount of traffic. We hope that our work may provide some insights useful for the design of routing protocols, and hence for complex communication systems.

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