Effective usage of random routing on networks of mobile agents

Gan-Hua Wu\textsuperscript{1,2} and Hui-Jie Yang\textsuperscript{1}

\textsuperscript{1}Business School, University of Shanghai for Science and Technology, Shanghai 200093, China
\textsuperscript{2}School of Software, South China Normal University, Guangzhou 510641, China

Most existing routing strategies to improve transport efficiency have little attention what order should the packets be delivered, just simply used first-in-first-out queue discipline. However, it is far from optimal. In this paper we apply priority queuing discipline to random routing strategy on networks of mobile agents, in which the packets have high priority to transfer directly to their destination despite their order in the queue if their destination are within a communication radius. Numerical experiments show that it not only remarkably improves network throughput and the packet arriving rate, but also reduces average travelling time and the rate of waiting time to travelling time. Our work may be helpful in routing strategy designing on networks of mobile agents.

PACS numbers: 89.75.Hc, 89.40.-a, 05.40.Fb

1. Introduction

Traffic process exists widely in natural, engineering, and social systems\cite{1}. For instance, the mass flux in metabolic networks\cite{2}, information transfer over internet\cite{3}, and the transportation on airlines\cite{4}. An essential challenge is how to archive a fluent traffic, i.e., the transportation is routed immediately and speedy without a congestion.

Persistent efforts result in various versions of routing methods\cite{5,6,7,8}. Some are called hard strategies, in which the traffic is optimized by adjusting topological structures of traffic networks. Modification of local pattern, such as removing some links from hubs\cite{9} or betweenness\cite{10}, or adding some shortcut links\cite{11}, can enhance effectively the routing capacity. However, in reality it is generally costly or even impossible to adjust topological structure.

The others are called soft protocols, in which different methods for redistribution of packages are designed. In the well-known shortest path....
protocol\cite{12} a packet walks to its destination along the shortest path. However, a simply implementation of this method will lead to a high-traffic flow on the bottlenecks, i.e., most packets tend to pass through the links with high betweenness\cite{13}. Besides the shortest path length, improved versions consider also the node degrees\cite{14,15}, node/link load\cite{16,17}, next-nearest neighbors\cite{18,19}, memory information\cite{20}, and so on.

With the development of mobile technology, networks of mobile agents are widely used. A typical example is mobile ad-hoc network, in which agents move randomly and two agents can transfer data packets with each other only when the distance between them is less than a critical value\cite{21,22}. As network structure changes frequently with agents move, previous routing strategies on static networks can not apply directly to networks on mobile agents. Moreover, routing strategies on networks of mobile nodes have attracted little attention in the physics community. Recently Yang et al. proposed a random routing strategy based on first-in-first-out discipline on networks of mobile agents, in which packets in first-in-first-out principle are sent to the destination directly and removed immediately from the system packets if theirs destination are within a communication radius, otherwise they will be delivered to a randomly selected neighbour agent. They found an algebraic power law between the throughput and the communication range with an exponent determined by the speed\cite{23}.

In previous studies, the first-in-first-out queuing protocol is widely used, namely, the coming packets that are not delivered immediately to the destination will queue in the buffer of a node according to the order of arrival, and the node will deliver first a packet coming first. It is simple and convenient, but far from optimal. An alternative protocol is priority schemes\cite{24}, in which packets are given priorities, the ones with higher priorities to be selected ahead of those with lower priorities, regardless of their time of arrival. For example, paid packets with high priority are delivered first when downloaded from a certain web site.

However, only a few articles use priority discipline. Kim et al. introduce first a priority routing strategy to traffics on network models and simulate the jamming transitions, in which every packet is pre-set a priority. The traffic behavior is improved in the congestion region, but worsened in the free flow region\cite{25}. Tang and Zhou define an effective distance by considering simultaneously the waiting time and remaining path-length to the destination, according to which the packets queue in a descending order of the effective distance. It turns out to enhance remarkably the overall throughput of the network\cite{26}. Du et al. propose a shortest-remaining-path-first queuing strategy in which a packet’s priority is determined by the distance between its current location and destination. They found that although the network capacity has no evident changes, the traffic efficiency is greatly
improved, especially in the congestion state. Zhang et al. introduce a dynamic-information-based queueing strategy into network traffic model under the efficient routing strategy, which leads to no obvious change to network capacity, but significant improvement of some other traffic indexes such as average travelling time, rate of waiting time to travelling time.

In previous studies, few researchers have applied priority discipline to routing strategy on networks of mobile agents. In this article, we propose random routing strategy embed priority queuing discipline, in which the packets have high priority to transfer directly to their destination despite their order in the queue if their destination are within a communication radius, otherwise packets are delivered to a randomly selected neighbour agent in first-in-first-out order. Compared with the random routing strategy based on first-in-first-out discipline, in this strategy a packet in the queue has more chance to be removed directly, which reduces effectively the load of the whole system and subsequently improves the network’s capacity, as confirmed by our simulations.

2. Methods and Materials

2.1. Network structure and routing strategy

Traffic is simulated on a random network of mobile agents, i.e., $N$ agents (numbered from 1 to $N$) move on a square-shaped cell of size $L \times L$. Periodic boundary condition is used. Initially, agents distribute randomly in the area. At each time step $\Delta t = 1$, moving direction of an agent is re-directed randomly, while its speed $v$ is selected to be a constant for simplicity. Let $\theta_i(t)$ be the angle of moving direction of the $i$th agent at time $t$ with respect to x-axis, generated by sampling from a uniform distribution in $[-\pi, \pi]$, $x_i(t)$ and $y_i(t)$ its the coordinates. The distribution of the mobile agents evolves according to,

$$
\begin{align*}
    x_i(t+1) &= x_i(t) + v \cos \theta_i(t), \\
    y_i(t+1) &= y_i(t) + v \sin \theta_i(t),
\end{align*}
$$

At each time step, a total of $R$ packets are generated in the network, whose source and destination are randomly selected. All the agents have a same communication radius $\alpha$. Two agents can transfer packets with each other only when the distance between them is less than $\alpha$. A agent can deliver at most $C$ packets per time step, which is assigned to be 1 in our calculations. The queue length of each agent is assumed to be unlimited.

In our strategy, to transport a packet in each time step, the agent checks every packet in the queue from head to tail, if its destination is within a
communication radius, the packet have highest priority and transfer directly to its destination despite their order in the queue and removed immediately from the system, until the removed number reaches $C$. If the removed number are less then $C$, packets are delivered to randomly selected neighbour agent in first-in-first-out order until a total of $C$ packets are processed or the buffer becomes empty.

2.2. Critical packet generating rate

In the present work the traffic is determined by two competitive factors. The one is the removing packets determined by routing strategy, the communication radius, density of agents, moving speed, and the number of packets transferred. The other is the number of packets produced each time step. When the generating rate of packets is small, new packets can arrive quickly their destination, the load will keep unchanged or even zero, called a free-flow state. When the rate increases to a certain value, averagely at each time step there appear some new packets that can not be delivered to their destination on time. This aggregation of new packets will increases rapidly the load of the network. In reality, a network has a limited capacity, a persistent overload on which will lead to onset of a congestion, i.e., a collapse of the system. To characterize the throughput of a network, we exploit the order parameter $\eta$ introduced in Ref [29],

$$\eta(R) \equiv \lim_{t \to \infty} \frac{C}{R} \frac{N_p(t + \Delta t) - N_p(t)}{\Delta t} = \lim_{t \to \infty} \frac{C}{R} (N_p(t + 1) - N_p(t)), \quad (2)$$

where $N_p(t)$ represents the total number of packets existing in the whole network at time $t$. When $R$ is less than a critical value of $R_c$, there is a balance between the generated and removed packets, which implies $\eta(R) = 0$. When $R$ becomes larger than $R_c$, a transition occurs from a free-flow state to a congestion state. A higher $R_c$ corresponds to a better algorithm.

2.3. Average travelling time

Travelling time refers to a packet to travel from its source to destination. Average travelling time is defined as,

$$< T > = \frac{\sum_{i=1}^{N_{\text{arrive}}} T_i}{N_{\text{arrive}}}, \quad (3)$$

where $T_i$ represents travelling time of packet $i$, $N_{\text{arrive}}$ are the number of arrived packets. Average travelling time $< T >$ is an important measurement of a network’s performance. In real communication networks, packets have
a finite life time to avoid wasting the network resources\cite{30, 31}. For example, an error of packet’s destination may cause the packet to be transmitted endlessly. Therefore, if a packet has been transferred more than finite life time, it will be removed from the networks even if it has not achieved its destination. Obviously, a lower value of $< T >$ corresponds to a better algorithm.

2.4. The rate of waiting time to travelling time

The rate of waiting time to travelling time is defined as

$$W = \left( \sum_{i=1}^{N_{\text{arrive}}} \frac{T_{i-\text{wait}}}{T_{i-\text{travel}}} \right) / N_{\text{arrive}},$$

(4)

where $T_{i-\text{travel}}$ is the travelling time of packet $i$, $T_{i-\text{wait}}$ is the waiting time of packet $i$, and $N_{\text{arrive}}$ is the number of arrived packets. In general, $W$ reflects the degree of customer satisfaction\cite{27}. In many systems, such as airlines systems and the World Wide Web, users become impatient if $W$ is large.

2.5. Packet arriving rate

Packet arriving rate reflects to the number of generated packets divided by the number of arrived packets, namely,

$$A = \frac{N_{\text{arrive}}}{N_{\text{generate}}},$$

(5)

where $N_{\text{arrive}}$ is the number of arrived packets and $N_{\text{generate}}$ the number of generated packets. Obviously, $A$ is an index of system throughput. In the free-flowing state, the generated packets are delivered to the destination and removed on time, so $A$ is quite close to 1, while in the congestion state, the generated packets accumulate in the network and can not be distributed timely, thus $A$ is smaller than 1.

3. Results

Initially, a total of 1000 agents are positioned randomly on a square of $10 \times 10$. Figure 1 shows two typical results of $\eta$ versus $R$ with a selection of $\alpha = 1.3$, $C = 1$, at low ($v = 0.2$) and high ($v = 2$) moving speed respectively. For each specific case, there exists a finite value of $R_c$, at which a transition from free-flow to congestion occurs in a sharp interval of $R$. For description convenience, we represent the rapid increase of $\eta$ by using $R_c$ at which $\eta$ starts to be non-zero. We can see the $R_c$ of random routing...
strategy embed priority queuing discipline is significantly larger compared with that of random routing strategy embed first-in-first-out queuing discipline. For instance, when $v = 0.2$, $R_c$ of the random routing strategy embed first-in-first-out queuing discipline is 25, which increases to $\sim 800$ of the random routing strategy embed priority queuing discipline. Obviously, the random routing strategy embed priority queuing discipline improves remarkably network throughput.

Figure 2 shows the dependence of $R_c$ on $v$ at different values of $\alpha$. The number of agents is selected to be 500 and 1000 respectively. The two strategies share two characteristics, one of which is that the curve of $R_c$ versus $v$ increases rapidly and converges to a constant, the other of which is that the
Fig. 2. The logarithmic critical packet generating rate $R_c$ against $v$ for different $\alpha$, here $L = 10, C = 1$. PQS represents priority queueing strategy, FIFO represents first-in-first-out strategy.

reached constant increases when the total number of agents becomes large. Comparatively, $R_c$ of the random routing strategy embed priority queueing increases faster and converges to a larger value. What is more, $R_c$ of the random routing strategy embed priority queueing converges to a large value of $\sim 450$ which is independent with $\alpha$, while that of the random routing strategy embed first-in-first-out queuing discipline converges to small but different values at different selection of $\alpha$ (3, 21 and 50 at $\alpha = 0.6, 1.3$, and 2 for the case of $N = 500$, respectively).

Figure 3 represents the dependence of average travelling time $< T >$ on $R$, and the insert shows that in the free-flow state ($R < R_c$) with a low ($v = 0.2$) and a high ($v = 2$) moving speed. One can find $< T >$ of two strategies increases as $R$ increases, and $< T >$ of priority queueing strategy is lower than that of first-in-first-out strategy in both free-flow state and congestion state.

Figure 4(a) and 4(b) show the dependence of the rate of waiting time to travelling time $W$ and the packet arriving rate $A$ on $R$, respectively. From Fig. 4(a), $W$ of two strategies is close to 0 when $R$ is small, and with $R$ increase, $W$ increases quickly, when $R$ increases to $\sim 70$, $W$ of the first-in-first-out strategy is close to the maximal value 1, while that of the priority
Fig. 3. The logarithmic average travelling time $< T >$ as a function of the packet-generation rate $R$. The inset shows $< T >$ as a function of $R$ when $R < R_c$. Here $N = 1000$, $L = 10$, $C = 1$, and $\alpha = 1.3$. PQS represents priority queueing strategy, FIFO represents first-in-first-out strategy. 

queuing strategy is just $\sim 0.65$ and $\sim 0.54$ at $v = 0.2$ and $2$, respectively. From Fig. 4(b), the packet arriving rate $A$ of the two strategies is close to 1 in free-flow state, while in the congestion state, $A$ of the first-in-first-out strategy decreases more quickly than that of the priority queueing strategy. When $R$ increases to $\sim 1000$, $A$ of the first-in-first-out queueing strategy is close to the minimal value 0 while that of the priority queueing strategy is $\sim 0.9$ and $\sim 0.97$ at $v = 0.2$ and $2$, respectively. It is obvious that the priority queueing strategy can achieve higher value of packet arriving rate and get lower value of the rate of waiting time to travelling time than the first-in-first-out queueing strategy.
Fig. 4. (a) The rate of waiting time to travelling time $W$ as a function of the packet-generation rate $R$. (b) The packet arriving rate $A$ as a function of the packet-generation rate $R$. Here $N = 1000$, $L = 10$, $\alpha = 1.3$, and $C = 1$. PQS represents priority queueing strategy, FIFO represents first-in-first-out strategy.

4. Conclusions

Transportation dynamics on complex networks have been studied extensively due to their practical significance in real communications networks. However, few researchers have considered queue discipline when they propose routing strategy, just simply used first-in-first-out queue discipline. In the present work we apply priority queuing discipline to random routing strategy on networks of mobile agent, in which packets whose destination are reachable are delivered first, the left packets in first-in-first-out queuing discipline are transferred randomly to the agents within a communication circle.

Compared with the random routing strategy based on first-in-first-out principle, our proposal has a significant high performance, measured by not only a large value of critical packet generating rate and packet arriving rate, but also a significant small value of average travelling time and the rate of waiting time to travelling time. It is worth mentioning that the priority
queue discipline can be applied to other routing strategies. Our work may be helpful in routing strategy designing on networks of mobile agents.

REFERENCES

[1] S. Y. Chen, W. Huang, C. Cattani, and G. Altieri, *Math. Probl. Eng.* **2012** (2011) 23.
[2] A. E. Motter, N. Gulbahce, E. Almaas, and A. L. Barabási, *Mol. Syst. Biol.* **4** (2008) 168.
[3] R. P. Satorras, A. Vázquez, and A. Vespignani, *Phys. Rev. Lett.* **87** (2001) 25.
[4] D. Bertsimas and S. S. Patterson, *Transport. Sci.* **34** (2000) 239.
[5] P. Echenique, J. G. Gardeñes, and Y. Moreno, *Europhys. Lett.* **71** (2005) 325.
[6] W. B. Du, X. L. Zhou, M. Jusup, and Z. Wang, *Sci. Repts.* **6** (2016) 19059.
[7] R. W. Niu and G. J. Pan, *Chin. J. Phys.* **54** (2016) 278.
[8] A. S. Ribalta, S. Gómez, and A. Arenas, *Phys. Rev. Lett.* **116** (2016) 108701.
[9] Z. Liu, M. B. Hu, R. Jiang, W. X. Wang, and Q. S. Wu, *Phys. Rev. E* **76** (2007) 037101.
[10] G. Q. Zhang, D. Wang, and G. J. Li, *Phys. Rev. E* **76** (2007) 017101.
[11] W. Huang and T. W. S. Chow, *Chaos* **20** (2010) 033123.
[12] B. Awerbuch, *Comput. Commun. Rev.* **20** (1990) 4.
[13] B. Danila, Y. Yu, J. A. Marsh, and K. E. Bassler, *Phys. Rev. E* **74** (2006) 046106.
[14] G. Yan, T. Zhou, B. Hu, Z. Q. Fu, and B. H. Wang, *Phys. Rev. E* **73** (2006) 046108.
[15] W. X. Wang, B. H. Wang, C. Y. Yin, Y. B. Xie, and T. Zhou, *Phys. Rev. E* **73** (2006) 026111.
[16] P. Echenique, J. G. Gardeñes, and Y. Moreno, *Phys. Rev. E* **70** (2004) 056105.
[17] X. Ling, M. B. Hu, R. Jiang, and Q. S. Wu, *Phys. Rev. E* **81** (2010) 016113.
[18] B. Tadić and S. Thurner, *Physica A* **332** (2004) 566.
[19] S. J. Yang, *Phys. Rev. E* **71** (2005) 016107.
[20] W. Huang and W. S. Chow, *Chaos* **19** (2009) 043124.
[21] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, *Ad Hoc Netw.* **2** (2004) 1.
[22] T. Camp, J. Boleng, and V. Davies, *Wirel. Commun. Mob. Comput.* **2** (2002) 483.
[23] H. X. Yang, W. X. Wang, Y. B. Xie, Y. C. Lai, and B. H. Wang, *Phys. Rev. E* **83** (2011) 016102.
[24] D. Gross, J. F. Shortle, J. M. Thompson, and C. M. Harris, in *Fundamentals of Queueing Theory*, ed. D. J. Balding et al. (John Wiley & Sons, Hoboken, 2008), p. 15.
[25] K. Kim, B. Kahng, and D. Kim, *Europhys. Lett.* **86** (2009) 58002.
[26] M. Tang and T. Zhou, Phys. Rev. E 84 (2011) 026116.
[27] W. B. Du, Z. X. Wu, and K. Q. Cai, Physica A 392 (2013) 3505.
[28] X. J. Zhang, X. M. Guan, D. F. Sun, and S. T. Tang, Commun. Theor. Phys. 60 (2013) 496.
[29] A. Arenas, A. D. Guílera, and R. Guimerà, Phys. Rev. Lett. 86 (2001) 3196.
[30] C. L. Chen, X. B. Cao, and W. B. Du, Physica A 389 (2010) 4571.
[31] W. B. Du, X. B. Cao, C. L. Chen, and G. Yan, Physica A 390 (2011) 3982.