Efficient priority queueing routing strategy on networks of mobile agents

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As a consequence of their practical implications for communications networks, traffic dynamics on complex networks have recently captivated researchers. Previous routing strategies for improving transport efficiency have paid little attention to the orders in which the packets should be forwarded, just simply used first-in–first-out queue discipline. Here, we apply a priority queueing discipline and propose a shortest-distance-first routing strategy on networks of mobile agents. Numerical experiments reveal that the proposed scheme remarkably improves both the network throughput and the packet arrival rate and reduces both the average traveling time and the rate of waiting time to traveling time. Moreover, we find that the network capacity increases with an increase in both the communication radius and the number of agents. Our work may be helpful for the design of routing strategies on networks of mobile agents.

Keywords: Traffic dynamics; network of mobile agents; shortest-distance-first queueing strategy.

1. Introduction

Engineering and social systems exhibit widespread traffic issues,¹ typical examples of which include the delivery of information over the World Wide Web and transportation within highway systems.^{2,3} Rapid societal development throughout the world has led to an enormous increase in the traffic volume in many network communication systems.⁴ The enhancement of the transport efficiency of modern

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networks, then, constitutes a fundamental challenge. The optimal performance of a network depends primarily on its structural characteristics and on the routing strategy.⁵ However, as the structures of existing networks such as the Internet have been fixed, they are difficult to change even though they are far from optimal. Hence, additional effort must be taken to improve the transport efficiency in existing routing strategies.

Routing strategies based on the shortest path algorithm are widely used in real communication systems.⁶ When employing the shortest path strategy, a packet will walk to its destination along the shortest available path. However, this will easily induce congestion at hub nodes since most packets tend to pass through the links with a high betweenness.⁷ This issue has consequently motivated researchers to propose many improved versions of the strategy in consideration of either global or local information. For example, Yan *et al.* proposed an efficient routing strategy in which each node contains the global topological information in the network.⁸ They found that the network capability can be improved by more than 10 times by optimizing the efficient path. However, a strategy based on global information may be practical for small or medium-sized networks, but it is not applicable to large communication systems such as the Internet or the World Wide Web due to their large storage capacities at each node and the substantial communication cost associated with searching for global information within the network.⁹

Therefore, scientists proposed numerous other strategies based on local information. Wang *et al.* proposed a local information routing strategy in which packets are routed based solely upon local topological information using a tunable parameter β according to the neighbors degree of each node. They found that the maximal capacity corresponds to $\beta = -1$ for the delivering ability of identical nodes.¹⁰ Tadić and Rodgers first introduced the next-neighboring-search algorithm in Ref. 11. They found long-range correlations in the power spectra of arriving packet density and the network's activity bursts. Liu *et al.* proposed an adaptive local routing strategy based on real-time load information in which a node adjusts the forwarding probability using the dynamical traffic load (i.e. the packet queue length) and the degree distribution of neighboring nodes. They discovered that their algorithm can improve the transmission capacity by reducing the number of routing hops.¹² Furthermore, Wang *et al.* proposed a mixing routing strategy which when, compared with strategies that exclusively adopt local static information can improve the efficiency of a network by integrating the degree of a node and the number of packets with a given parameter.¹³

Coincident with the development of mobile technology, networks of mobile agents are being widely used. A typical example is a mobile *ad hoc* network, in which the 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.^{14,15} Yang *et al.* proposed a random routing strategy on networks of mobile agents, in which the packets are delivered to a randomly selected agent within a communication circle. They found an algebraic power law between the throughput and the

communication range with an exponent determined by the speed.¹⁶ Moreover, Yang and Tang proposed an adaptive routing strategy which incorporates geographical distance with local traffic information through a tunable parameter. They discovered that an optimal value exists for the tunable parameter that leads to the maximum traffic throughput of the network.¹⁷

Previous studies paid little attention to queue discipline in routing strategies. Queue discipline refers to the manner in which packets are selected when the number of arrival packets exceeds the maximum processing capacity of the agent.¹⁸ The most common discipline is the first-in-first-out discipline. The second discipline is the last-in-first-out discipline, a typical example of which is a queue in which the last-clicked information in the World Wide Web is served first. The third discipline is a priority scheme, in which packets are given priorities, packets with a higher priority are selected prior to those with lower priorities regardless of the time that they arrive to the agent. For example, paid packets with a higher priority are delivered first when downloaded from a web site.

The first-in-first-out discipline, which is simple but far from optimal, is broadly utilized for most existing research. To the best of our knowledge, only few papers listed below have employed other disciplines. Tadić *et al.* studied the web-graph model using the last-in-first-out discipline.^{19–22} Kim *et al.* introduced a priority routing strategy in which each packet is pre-established with a priority, and they found that the traffic behavior is improved within congestion region but worsened in free-flow region.²³ Tang and Zhou defined an effective distance by simultaneously considering the waiting time and the remaining path length to the destination, based upon which the packets are queued in a descending order of the effective distance. They found that their proposed scheme can remarkably enhance the network throughput.²⁴ Meanwhile, Du *et al.* proposed a shortest-remaining-path-first queueing strategy in which the priority of a packet is determined by the distance between its current location and its destination, and they found that their strategy can greatly improve the traffic efficiency, especially for a congested state.²⁵ In addition, Zhang *et al.* proposed a dynamic-information-based queueing strategy, with which they discovered no obvious change in the network capacity, however, they did observe a significant improvement in some traffic indexes such as the average traveling time and the rate of waiting time.²⁶

To the best of our knowledge, researchers have not applied a priority discipline to the routing strategy for a network of mobile agents. However, the packets in a real dynamic network are often assigned a priority. For example, important military information often has a higher delivery priority on mobile *ad hoc* networks within a battlefield environment. In this paper, we propose a shortest-distance-first (SDF) queueing strategy in which a packet is delivered first if the distance between the location of a neighboring agent and its destination is the shortest path. Our primary results are as follows. First, compared with the first-in-first-out queueing strategy, our strategy not only remarkably improves the network throughput and the packet arrival rate but also reduces the average traveling time

and the rate of waiting time to traveling time. Second, we find that the network congestion is postponed to a more substantial density in the SDF queueing strategy and that the traffic parameters are improved with an increase in the moving speed of the agents. Finally, we find that the network capacity increases with an increase in both the communication radius and the number of agents for both strategies.

2. Methods and Materials

2.1. Network model and queueing strategies

Various mobility models have been proposed. Some examples of popular mobility models are the random walk model, the random way point model, and the mobility vector model.¹⁵ Each of these models has its own characteristics, working capacity and limitations. Here, we use the random walk model and establish the model parameters according to a previous paper on this model.¹⁶ In this study, N agents (numbered from 1 to N) move throughout a square-shaped cell of size $L \times L$. A periodic boundary condition is employed. Initially, agents are distributed randomly throughout the area. The moving direction of each agent is randomly redirected at each time step Δt while its speed v is selected as a constant for simplicity. At the same time, a total of R packets are generated within the network, whose source and destination are randomly selected. All of the agents have an identical communication radius α . Two agents can achieve communication with each other only when the distance between them is less than α .

The queuing strategies are described in the following steps.

- (1) To establish the parameters, set the number of agents to $N = 800$, the delivery capability of each node to $C = 1$, the time step as $\Delta t = 1$, the total simulation time as $T = 5000$, and the queue buffer of each agent as unlimited.
- (2) At each time, a total of R packets with random sources and destinations are generated within the network.
- (3) Update the positions of the mobile agents as follows:

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

where $i = 1, 2, \dots, N$, $\theta_i(t-1)$ is the angle of moving direction of the i th agent at the time $t-1$ with respect to the x -axis, generated by sampling from a uniform distribution in $[-\pi, \pi]$, and $x_i(t)$ and $y_i(t)$ are the coordinates of the i th agent at a time t .

- (4) For each agent, take M packets from the queue. Let the number of packets in the queue be K .
 - (a) shortest-distance-first queueing strategy: $M = K$,
 - (b) first-in-first-out queueing strategy: if $C > K$, then $M = K$; otherwise, $M = C$.

- (5) For each agent, first check the M packets in the normal order. If the destination of a packet is within its communication radius, the packet is sent directly to the destination and immediately removed from the system, then set $C = C - 1$. If $C = 0$, go to step (2) for the next T .
- (6) For a packet m in the system, $D_m(t)$ is defined as the shortest distance between the location of the neighboring agent and the destination of the packet, namely,

$$D_m(t) = \min_{k \in K} \sqrt{[x_k(t) - x_l^m(t)]^2 + [y_k(t) - y_l^m(t)]^2}, \quad (2)$$

where $m = 1, 2, \dots, M$ represents the packet of an agent i , K is the set of neighbors of agent i , $x_k(t)$ and $y_k(t)$ represent the coordinates of the neighbor agent k at time t , and $x_l^m(t)$ and $y_l^m(t)$ are the coordinates of the packet's destination at the time t .

- (7) If there are no more than C packets in the queue, all of the packets are sent to their neighboring agents according to $D_m(t)$; otherwise,
 - (a) shortest-distance-first strategy: the first C packets are delivered according to $D_m(t)$ in ascending order,
 - (b) first-in-first-out strategy: the first C packets are delivered in the normal order.
- (8) Repeat steps (4)–(7) for each agent.
- (9) Repeat steps (2)–(8) T times.
- (10) Compute the order parameter $\eta(R)$, the critical packet generating rate R_c , the average traveling time $\langle T \rangle$, and all other necessary parameters.

Note that the proposed algorithm is similar to the shortest-remaining-path-first queueing strategy proposed by Du *et al.*²⁵ The significant difference, however, is that the shortest-remaining-path-first queueing strategy was introduced for a scale-free network, in which the paths are fixed by wired links and the “shortest” path denotes the path with the smallest number of links between the source and the destination. On the other hand, the SDF scheme that we consider in this work uses the geographical distance to determine the shortest distance between the neighbor and target in a wireless mobile network. In the SDF strategy, a packet is transferred to a neighboring agent which is closest to the destination, and thus, can more easily reach the destination node.

2.2. Critical packet generating rate

In present-day research, the traffic is determined by two competitive factors, namely, the packets that are being removed, which are determined by the routing strategy, the communication radius, the agent density, the moving speed, the number of packets being transferred, and the number of packets produced at each time step. When the packet generating rate is small, new packets can arrive at their destination more quickly and the load will remain unchanged or go to zero, this is known as a free-flow state. When the rate increases to a certain value, some new packets

will appear on average at each time step, but they will not be delivered to their destination on time. This aggregation of new packets will rapidly increase the load of a network. In reality, since a network has a limited capacity, a persistent overload of that network will lead to the onset of congestion, i.e. a collapse of the system. To characterize the throughput of a network, we exploit the order parameter η introduced in Ref. 26:

$$\eta(R) \equiv \lim_{t \rightarrow \infty} \frac{C}{R} \frac{\langle N_p(t + \Delta t) - N_p(t) \rangle}{\Delta t} = \lim_{t \rightarrow \infty} \frac{C}{R} \langle N_p(t + 1) - N_p(t) \rangle, \quad (3)$$

where $N_p(t)$ represents the total number of packets existing in the whole network at the time t . When R is less than the critical value R_c , there is a balance between the packets being generated and those being removed, which implies that $\eta(R) = 0$. When R becomes larger than R_c , the number of packets $N_p(t)$ increases with the time t , implying that $\eta(R) > 0$, and a transition will occur from a free-flow state to congestion. In general, a higher threshold R_c corresponds to a better algorithm.

2.3. Average traveling time

The traveling time refers to the time required for a packet to travel from its source to its destination. The average traveling time is hence defined as

$$\langle T \rangle = \left(\sum_{i=1}^{N_{\text{arrive}}} T_i \right) / N_{\text{arrive}}, \quad (4)$$

where T_i represents the traveling time of a packet i , and N_{arrive} is the number of packets that have arrived. The average traveling time $\langle T \rangle$ is another important measurement of the performance of a network.^{28,29} Smaller values of $\langle T \rangle$ correspond to a faster traffic velocity.

2.4. The rate of waiting time to traveling time

The rate of waiting time to traveling time is defined as

$$W = \left(\sum_{i=1}^{N_{\text{arrive}}} T_{i-\text{wait}} / T_{i-\text{travel}} \right) / N_{\text{arrive}}, \quad (5)$$

where $T_{i-\text{travel}}$ is the traveling time of packet i , $T_{i-\text{wait}}$ is the waiting time of packet i , and N_{arrive} is the number of packets that have arrived. In general, W reflects the degree of customer satisfaction.²⁵ In many systems (e.g. airline systems and the World Wide Web), users often become impatient if the value of W is large.

2.5. Packet arrival rate

The packet arrival rate reflects the number of generated packets divided by the number of arrived packets, and it is defined as

$$A = N_{\text{arrive}} / N_{\text{create}}, \quad (6)$$

where N_{arrive} is the number of packets that have arrived and N_{create} denotes the number of generated packets. Obviously, A is an index of the system throughput. In a free-flowing state, the generated packets are sent to the destination on time, and thus, A is nearly equal to 1; meanwhile, in a congested state, the packets being generated will accumulate within the network and will not be distributed on time, and thus, A is smaller than 1.

3. Results

Two typical results of η versus R with a selection of $\alpha = 1$ at low ($v = 0.1$) and high ($v = 1$) moving speeds are shown in Fig. 1. For each specific case, there exists a finite value of R_c at which a transition from a free-flow state to congestion occurs over a sharp interval of R . For the sake of convenience, we represent the increase in η by using R_c , at which η starts as nonzero. We find that the threshold R_c for the SDF strategy is larger than that for the first-in-first-out strategy, especially at high moving speeds. In fact, the value of R_c for the first-in-first-out queuing strategy is ~ 30 at $v = 1$, while that for the SDF strategy is ~ 700 . Obviously, the SDF strategy remarkably improves the network throughput.

The dependence of R_c on v at $\alpha = 1$ is displayed in Fig. 2(a), and Fig. 2(b) shows the relationship between R_c and α at $v = 0.3$. Evidently, the threshold R_c for the SDF strategy is larger than that for the first-in-first-out queuing strategy for a different speed v and communication radius α . As demonstrated in Fig. 2(a), the value of R_c using the SDF strategy increases rapidly with an initial increase in

Fig. 1. (Color online) Order parameter η versus R for different values of speed v . The number of agents is 800, the size of the square region $L \times L = 10 \times 10$, the communication radius $\alpha = 1$, and the delivery capacity of each agent is $C = 1$. Each data point results from an average over 20 realizations. Error bar is not shown as the values of error are very small.

Fig. 2. (Color online) (a) The critical value R_c as a function of the moving speed v for the communication radius $\alpha = 1$. (b) The critical value R_c as a function of α for moving speed $v = 0.3$. The size of the square region $L \times L = 10 \times 10$ and the delivery capacity of each agent is $C = 1$.

v and then remains stable (~ 700 and ~ 1050 for $N = 800$ and 1200 , respectively) for v values greater than 0.7 . Meanwhile, the value of R_c using the first-in-first-out queuing strategy increases with an increase in v and reaches a maximum at $v = 0.1$, after which it decreases slowly. The R_c values using these two strategies (shown in Fig. 2(b)) increase as the communication radius α increases, but the R_c for the shortest-distance-first strategy increases faster than that for the first-in-first-out queuing strategy. As the communication radius increases, the packet transmission distance becomes larger, leading to an increase in the number of neighboring agents, and thus, the packets have a greater number of transmission paths to choose from and can consequently reach their destination more quickly. This is why R_c increases with α . We also find that R_c increases with an increase in the number of agents for different moving speeds and communication radius. Similarly, increasing the number of agents increases the number of neighbors within the communication radius, thereby increasing the value of R_c .

We further compare our strategy with the random routing strategy, which is a typical algorithm based on first-in-first-out rule on dynamic networks.¹⁶ The results reveal that our strategy can remarkably improve the network capacity. For example, when $N = 1200$, $L = 10$, $C = 1$, and $\alpha = 1$, the R_c values using our strategy are ~ 200 and ~ 1000 at speeds of $v = 0.1$ and 1 , respectively, while those obtained using the random routing strategy are ~ 10 and ~ 30 , respectively.

The dependence of the average traveling time $\langle T \rangle$ on R is displayed in Fig. 3, and the inset shows the same dependence in a free-flow state ($R < R_c$). We find

Fig. 3. (Color online) The average traveling time $\langle T \rangle$ as a function of the packet-generation rate R . The inset shows $\langle T \rangle$ as a function of R/R_c when $R < R_c$. The number of agents is 800, the size of the square region $L \times L = 10 \times 10$, the communication radius $\alpha = 1$, and the delivery capacity of each agent is $C = 1$.

Fig. 4. (Color online) (a) The rate of waiting time to traveling 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 . The number of agents is 800, the size of the square region $L \times L = 10 \times 10$, the communication radius $\alpha = 1$, the delivery capacity of each agent is $C = 1$, the time step $\Delta t = 1$, and the total simulation time $T = 5000$. Each data point results from an average over 20 realizations. Error bar is not shown as the values of error are very small.

that $\langle T \rangle$ increases for the two strategies as R increases. The inset indicates that the value of $\langle T \rangle$ for the SDF strategy is slightly lower than that for the first-in–first-out strategy in a free-flow state. However, from Fig. 3, the $\langle T \rangle$ for the SDF strategy is much lower than that of the first-in–first-out strategy in a congested state.

The dependencies of the rate of waiting time to traveling time W and the packet arrival rate A on R are respectively shown in Figs. 4(a) and 4(b). As demonstrated in Fig. 4(a), the value of W for both strategies is close to 0 when R is small, and W increases rapidly with an increase in R . When R increases to ~ 80 , the value W for the first-in–first-out strategy is close to the maximal value of 1, while that of the SDF strategy is just ~ 0.46 . The packet arrival rate A (Fig. 4(b)) for the two strategies in the free-flow state is close to 1, meanwhile, the value of A in a congested state for the first-in–first-out strategy decreases more rapidly than that for the SDF strategy. When R increases to 1000, the value of A for the first-in first-out queueing strategy is close to the minimal value of 0, while that for the SDF strategy is ~ 0.53 and ~ 0.8 at $v = 0.1$ and 1, respectively. Therefore, it is obvious that the SDF strategy can achieve a higher packet arrival rate and a lower value rate of waiting time to traveling time than the first-in–first-out queueing strategy.

4. Conclusions

Resolving the presence of traffic within mobile networks is a challenging endeavor. Unfortunately, routing strategies for networks of mobile agents have attracted little interest within the physics community. Moreover, previously proposed routing strategies paid little attention to the queue in which the packets should be forwarded and simply used the first-in–first-out queue discipline. Consequently, in this study, we propose a SDF queueing strategy in which the packets with the shortest distances are delivered first regardless of their arrival time. Our strategy can remarkably improve the network throughput relative to the first-in–first-out queueing strategy, especially when the agents move at high speeds. In addition, our strategy can increase the packet arrival rate and reduce both the average traveling time and the rate of waiting time to traveling time.

We also discover that the critical packet generating rate R_c for the first-in–first-out queueing strategy increases initially with an increase in the moving speed and reaches a maximum value at $v = 0.1$, after which it decreases slowly; meanwhile, the value of R_c for the SDF queueing strategy increases until $v = 0.7$ and remains stable thereafter. In addition, the R_c values for both strategies increase with an increase in both the communication radius and the number of agents. Finally, it should be noted that this priority queue discipline can be applied to other routing strategies. Our work may thus be helpful for the design of routing strategies for networks of mobile agents.

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