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Research on the search ability of Brownian particles on networks with an adaptive mechanism☆

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HIGHLIGHTS

- An adaptive mechanism for improving the search ability of random walks.
- Investigation on the influence of network topology on the mechanism.
- An absorption strategy to deal with the additional Brownian particles.

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ABSTRACT

In this paper, we focus on the search ability of Brownian particles with an adaptive mechanism. In the adaptive mechanism, nodes are allowed to be able to change their own accepting probability according to their congestion states. Two searching-traffic models, the static one in which nodes have fixed accepting probability to the incoming particles and the adaptive one in which nodes have adaptive accepting probability to the incoming particles are presented for testing the adaptive mechanism. Instead of number of hops, we use the traveling time, which includes not only the number of hops for a particle to jump from the source node to the destination but also the time that the particle stays in the queues of nodes, to evaluate the search ability of Brownian particles. We apply two models to different networks. The experiment results show that the adaptive mechanism can decrease the network congestion and the traveling time of the first arriving particle. Furthermore, we investigate the influence of network topologies on the congestion of networks by addressing several main properties: degree distribution, average path length, and clustering coefficient. We show the reason why random topologies are more able to deal with congested traffic states than others. We also propose an absorption strategy to deal with the additional Brownian particles in networks. The experiment results on Barabási–Albert (BA) scale-free networks show that the absorption strategy can increase the probability of a successful search and decrease the average per-node particles overhead for our models.

1. Introduction

The search process in networks is to find the useful information and establish optimal paths from sources to destinations. It has been shown that random walks is an efficient method for searching and routing strategies [1–4] and has attracted a great deal of attention in a variety of complex systems such as transport [5], communication [6,7], traffic [8–10], spreading [11], and so on. Since many complex systems can be efficiently described by a graph or a network, it allows us

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to investigate the searching performance of random walks on them by various methods inherited from the network theory and statistical physics.

In the search process of random walks, many parameters, such as access time and cover time [12], can be well addressed. Moreover, a variety of characteristics of the networks, such as the diameter [13], centrality [14], community structure [15], etc. can also be revealed by random walks. In recent years, several literature on networks have tackled the search ability of random walks [16–18] and design efficient routing strategies [19,20]. Based on the flow of a packet, many strategies proposed from a static perspective (i.e., packets are suggested to be forwarded using fixed routing strategies). Examples of such strategies include the random walks [21], the shortest path [22], the efficient path [19,20], the neighbor searching strategy [23], and the integration of static and dynamic information [24]. In addition, some congestion-aware mechanisms such as bypassing over-congested routes [25], rejecting information flow [26], and packet-dropping [25] are employed in these strategies for avoiding congestion of networks. However, these mechanisms are static and depend strongly on the congestion state of the whole network [4,23–26]. In order to improve the search ability of random walks, some researches have started to use multiple Brownian particles and proved it to be very efficient [17,18]. In particular, when the number of Brownian particles is set to be an appropriate large value, the first arriving particle can arrive at the destination almost along the shortest or nearly shortest paths. Unfortunately, these efficient methods that use multiple-Brownian particles are also static and ignore the congestion of networks, which is a very important factor that needs to be considered in practical applications. Recently, Shen et al. propose an adaptive strategy based on the linear prediction of queue length [27]. The strategy only focus on minimizing congestion in scale-free networks, and it depends greatly on the prediction orders which is difficult to be calculated [27].

In this paper, we focus on the search ability of Brownian particles with an adaptive mechanism that is proposed for avoiding congestion. In the adaptive mechanism, we allow nodes to be able to change their own accepting probability according to their own congestion states. In order to effectively describe the adaptive mechanism and test its performance, we propose two searching-traffic models, the static one in which the nodes have fixed accepting probability to the incoming particles, and the adaptive one in which the nodes have adaptive accepting probability to the incoming particles. A more realistic evaluation parameter, traveling time of a particle, which includes not only the number of hops for a particle to jump from the source node to its destination but also the time that the particle stays for in the queues of nodes, is used to evaluate the search ability of Brownian particles. We apply the two models to random networks, small world networks, and scale-free networks. The experiment results show that the adaptive mechanism can decrease the network congestion and the traveling time of the first arriving Brownian particles. Furthermore, we investigate the influence of network topologies on the congestion of networks by addressing the main properties: degree distribution, average path length, and clustering coefficient. We show the evidence for why random topologies are more able to deal with congested traffic states than others are. In the end, we propose an absorption strategy to deal with the additional Brownian particles in the networks. The experiment results on scale-free networks show that the absorption strategy can increase the probability of a successful search and decrease the average per-node particles overhead for our models.

2. The searching-traffic models for Brownian particles

2.1. The simple static searching-traffic model

In a network, the flow of Brownian particles between nodes can be considered as a probabilistic event [18]. If a particle at node i knows its destination, the probability for the particle to go from i to its neighbor j can be written as $p_{ij} = 1/k_i$, where k_i is the degree of node i. When the particle arrives at its destination, it will be removed from the network. Here, we use a set of evolution equations to describe the dynamics of the queue length of nodes q_i^t $(i = 1, 2, \ldots, N)$ at time t, where N is the number of nodes in the network. All the queues of nodes are FIFO (first in–first out) queues. In each time step from t to $t + 1$, node i tries to send a particle in its queue to any of its neighbors, and the particle will be accepted with probability η. If the particle is accepted by a neighbor of node i, it will be removed from the queue of node i. We assume that all the nodes can store as many particles as needed but can deliver a finite number of them at each time step. We set this number to be 1 for simplicity. For the simple static searching-traffic model, the η is fixed. Thus, at time t, the number of particles that successfully flow into node i is

$$n_{\text{in}}^t = \eta \sum_{j=1}^{N} \psi(q_j^t) A_{ji} p_{ji} \tag{1}$$

and the probability that a particle from node i is successfully delivered to the neighbors of node i is

$$n_{\text{out}}^t = \eta \sum_{j=1}^{N} \psi(q_i^t) A_{ij} p_{ij} \tag{2}$$

where $\psi(x)$ is the Heaviside step function that $\psi(x) = 1$ if $x > 0$ and $\psi(x) = 0$ otherwise. A_{ij} is the element in the adjacency matrix $\mathbf{A}$ of the network. $A_{ij} = A_{ji} = 1$ if there is an edge between nodes i and j and $A_{ij} = A_{ji} = 0$ otherwise.