



Traffic dynamics in scale-free networks with tunable strength of community structure

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ABSTRACT

In this paper we systematically investigate the impact of community structure on traffic dynamics in scale-free networks based on local routing strategy. A growth model is introduced to construct scale-free networks with tunable strength of community structure, and a packet routing strategy with a parameter α is used to deal with the navigation and transportation of packets simultaneously. Simulations show that the maximal network capacity stands at $\alpha = -1$ in the case of identical vertex capacity and monotonously decreases with the strength of community structure which suggests that the networks with fuzzy community structure (i.e., community strength is weak) are more efficient in delivering packets than those with pronounced community structure. To explain these results, the distribution of packets of each vertex is carefully studied. Our results indicate that the moderate strength of community structure is more convenient for the information transfer of real complex systems.

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1. Introduction

Complex networks can represent a wide range of complicated systems in nature and society, therefore the study on their structure and function has been a quickly growing interest in this area. Since Watts and Strogatz discovered the small-world (SW) phenomenon [1] and Barabási and Albert found scale-free (SF) degree distribution [2], the evolutionary mechanism of network structure and dynamic processes taking place upon the networks have led to many important contributions in a variety of scientific disciplines [3–7]. One focus of these studies is the interplay between traffic dynamics and network structure, which is becoming increasingly important for the large communication and transportation systems. On one hand some previous works show that the evolution of network structure is driven by the increment of traffic flow [8–10], on the other hand they contrarily explore that how different kinds of network structures affect the traffic dynamics [11–19].

The routing strategy based on the shortest path between vertices is widely used in the real communication networks such as Internet, which allows each vertex to have the global topology information of the network. Some models based on the global routing strategy are proposed to mimic the navigation and transportation of packets in a complex network by introducing the packets' generating rate and randomly selected source and destination [11,20–22]. In these models, the network capacity is defined by the critical generating rate (i.e. the critical phase), which determines the phase transition from free state to congestion. Under the critical generating rate, the network can balance the numbers of created and delivered packets which makes the load of the network stay at lower values, while over the critical generating rate, the network will congest as its load accumulates with time due to the limited delivering capacity or finite queue length of each vertex. During the critical phase, the free and jammed states coexist in the system. However, since the the rapid development of the size

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of real communication networks in modern society, the information that any one of the vertices has about the topology of network is incomplete. Thus, many experts focus on the distributed navigation using local information of the topology of the network. For instance, Zhou found that the mixing of the random walk and shortest path strategies can remarkably enhance the efficiency of navigation [23]. Boguñá et al. generated Internet-like scale-free networks with high navigability by embedding vertices into hyperbolic metric space and adding links between nearby vertices according to probability [24,25]. Zhuo et al. investigated that the navigation based on distance between vertices in the hidden metric space can efficiently deliver a message in a small-world network through a process of information exchange and accumulation [26].

On the other hand, it has been revealed that the community structure exists in these communication networks (e.g. Internet [27] and WWW [28–31]), in which a group of vertices from dozens to hundreds tend to make up a cluster and organize in a hierarchical way [32]. The community structure makes the generation and evolution of networked system much quicker and more stable than if the system is unstructured [33]. They also deeply affect the dynamics process occurring in a networked system. For instance, the synchronization process could be hindered when the networked system opposes the stronger community structure [34]. Understanding how messages pass through those networks with a community structure and the impact of community structure on information transfer capacity are also important and significant for real networked systems. The previous works [16,35] point out that community structure affects the navigability of messages, however, they didn't show that the traffic dynamics that simultaneously includes the navigation and transportation of packets was influenced by the community. Here we simulate it on the scale-free network with a tunable community strength and aim to quantitatively study the impact of the community on information transfer.

As both the packet routing strategy and network topology play essential parts in traffic flow, we systematically investigate the traffic dynamics on scale-free network with tunable strength of community structure combined with local routing strategy according to the degree of vertices. In the next section, we will describe the network construction and packet routing strategy. In Section 3, simulations and a few analytical results are presented in both free and jammed state. In the last section, we conclude our work.

2. The traffic model

As many real SF networks have an obvious community structure, we adopt a growth model to construct SF networks with tunable strength of community structure. Inspired by two ingredients of the Barabási–Albert (BA) model, i.e. growth and preferential attachment, the model is created as follows: We initialize completely connected networks with c communities noted by $U_1, U_2, \dots, U_c$, each of which has small number (m_0) of vertices. Every time, a new vertex is added into a certain community U_l with m ($m < m_0$) edges, where the n edges are linked to the vertices in community U_l and the other $m - n$ edges are linked to these in other $c - 1$ communities. Specifically, we first choose n different vertices in community U_l according to preferential attachment, which associates with the probability $\prod$ that a new vertex linking to vertex i ($i \in U_l$) relates to the degree k_i of vertex i , $\prod = k_i / \sum_{j \in U_l} k_j$. Then for each one of the other $m - n$ edges of the new vertex, we randomly choose a community U_h ($U_h \neq U_l$) and connect the new vertex to one vertex in community U_h following the aforementioned preferential attachment mechanism.

In our model, the degree distributions of vertices of both the whole network and each community obey the power law with exponent approximate 3 when the network size is $N = 10^3$ [36]. They are also independent of the strength of community that is quantified as [29,37]:

$$Q = \sum_{s=1}^c \left[\frac{l_s}{L} - \left(\frac{d_s}{2L} \right)^2 \right], \quad (1)$$

where c is the number of communities, L is the number of edges in the network, l_s is the number of edges in community U_s , and d_s is the sum of vertex degrees in community U_s . For large N , in Eq. (1), $L = mN$, $l_s = \frac{nN}{c}$, and $d_s = \frac{2mN}{c}$ [36]. Instead of Eq. (1), we obtain

$$Q = \frac{n}{m} - \frac{1}{c}. \quad (2)$$

Thus, by modulating m and n , the strength of community structure is tunable.

The traffic model is first proposed in Ref. [13], and to keep our description self-contained as possible, we briefly review the model: there are R packets are generated in the system at every time step, and each one chooses its source and destination randomly. The vertices can deal with at most C packets towards their destinations. A packet routing strategy that relates to the local topology information is used to navigate packets. Concretely, if the packet's destination is within the neighbor area of searching vertex, it will be delivered directly to its target. Otherwise, the searching vertex will navigate the packet to one of its neighbors with the preferential probability [13]:

$$\Pi_i = \frac{k_i^\alpha}{\sum_j k_j^\alpha}, \quad (3)$$

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