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Effects of community structure on navigation

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ABSTRACT

The dynamic behaviors of the complex network are crucially affected by its structural properties, which is an essential issue that has attracted much interest. In this paper, the effects of the community structure on the navigability of complex networks are comprehensively investigated. The networks we explored, each of which is embedded in a K-dimension Euclidean space based on a landmark based multi-dimensional scaling (LMDS) algorithm, are of scale-free configuration with tunable modularity, obtained by regulating the proportion of edges in and between communities. Pairs of source and target are selected from the nodes in the networks, and the messages are passed along from source to target in this space based on the greedy routing strategy. The extensive experiments we carried out suggest that, the higher navigability, defined by proportion of messages successfully delivered, is related to stronger modularity of the complex networks. In addition, the optimal dimension K of the embedding Euclidean space is found to be approximately identical to half of the landmark number.

1. Introduction

Navigation is one of the fundamental dynamical properties of networks. In the 1960s, a series of experiments conducted by Travers and Milgram [1] unveiled that messages could be delivered to a destination through only a few people in the large-scale social networks, in which nobody is aware of the whole information of the network structures. This phenomenon is known as the small-world (SW) property. Recently, the SW phenomenon further confirmed that about twenty percent of letters were successfully delivered with an average 4–5 hops in the experiments performed, both in email and online social service networks, based on a greedy routing strategy [2–4]. Moreover, networks from the fields of nature and technology also show similar properties revealed by several empirical works [5–7]. In light of the pervasiveness of the SW phenomenon in various kinds of networks, it turns out to be important to interpret this phenomenon, and work has been carried out. For instance, Watts and Strogatz [5] proposed a model of an SW network with characterization of low diameter and high cluster coefficient by adding random connections on a regular network. Following that, Kleinberg defined an infinite family of network models that naturally generalize the Watts–Strogatz model based on a decentralized algorithm, with which a high probability can be achieved to find short paths [8]. On the other hand, the investigation of navigation (e.g. passing messages) in complex networks has shown that the network topological properties, such as the SW property, the exponent of power-law distribution, and the number of long range connections have effects on their navigability [8–11].

The aforementioned SW structure and power-law degree distribution have described the global properties of network topology, however, the local environment of nodes in many real networks is also explored, such as the so-called community structure [12–17]. In general, a community is defined as a subset of nodes in which connections are dense and among

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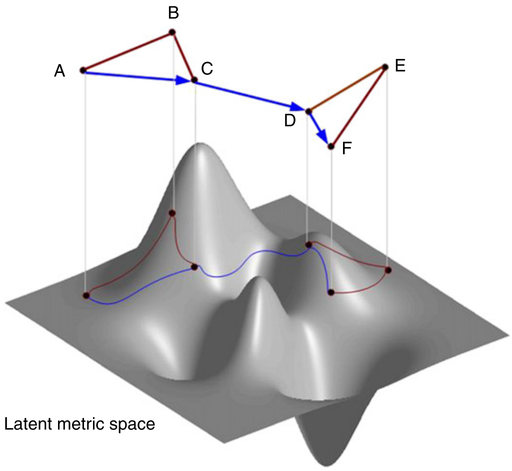

Fig. 1. (Color online) The illustration for embedding the network in latent metric space, which is similar to the definition of hidden metric space in Ref. [10].

which connections are sparse [18]. The community is an essential local property in a complex network, since some dynamic processes, like epidemic spread [19], synchronization [20,21], and traffic [22], are found to be highly affected by the community structure (see also in Refs. [23,24]). The effects of community structure on navigation, on the other hand, have not been fully studied, though the navigability of complex networks has been examined [8,10,25,26].

In this paper, based on scale-free networks with tunable modularity, we intend to provide an investigation on how community structure affects the navigation in the networks embedded in Euclidean space. The procedures of network construction and embedding are described respectively in the next section. In Section 3, we give the process of the designed experiments as well as the simulation results, and finally we conclude our work in the last section.

2. The network construction and embedding

In order to generate networks with community structure, we followed the procedure to construct a scale-free network model of communities in Ref. [20], in which the two key ingredients of the Barabási–Albert model, i.e., growth and preferential attachment [27] are adopted. The initial network is completely connected. Nodes are divided into c communities denoted by $U_1, U_2, \ldots, U_c$, each of which has small number (m_0) of nodes. A new node is added to one of the communities at each step with m ($m < m_0$) edges, where n edges are in the community and $m - n$ edges connect to the nodes in the remaining $c - 1$ communities. Edges within the community are connected according to preferential attachment associating with the probability Π that the new node belonging to U_l will connect to node i ($i \in U_l$) restricted to the degree k_i of node i, $\Pi(k_i) = k_i / \Sigma_{j \in U_l} k_j$. Then each of the other $m - n$ edges randomly chooses a community U_h ($U_h \neq U_l$) and connects the new node to one node in U_h following the preferential attachment mechanism referred to above. In this model, the mechanisms of growth and preferential attachment make the degree distributions of nodes in whole network and each community both obey the power law with exponent $\approx$3 when the scale N of the network is 10^3 [20].

The modularity proposed by Newman and Girvan [28] can be quantified by [29]

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

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, d_s is the sum of node degrees in community U_s. For large N, in Eq. (1), $L = mN$, $l_s = \frac{nN}{c}$, and $d_s = \frac{2mN}{c}$ [20]. Thus, in the above formation mechanism model, the calculation formula of Q can be simplified as:

$$Q = \frac{n}{m} - \frac{1}{c}. \tag{2}$$

By modulating m and n, we can obtain a series of scaling-free networks with different modularity. Note that here we set Q in a range from 0.2 to 0.8 in all experiments.

As the network is constructed, we define the navigability of a network as the ability that messages can be successfully delivered to targets by greedy routing strategy. To answer the question that how nodes evaluate the distance (or path length) between them for greedy routing strategy, we assume the existence of latent metric space and introduce its concept of latent metric space, i.e., each node of network is assigned a d-dimension coordinate of latent metric space based on a certain embedding algorithm. Other similar concepts of latent metric space have been studied and demonstrated in Refs. [30,31]. As shown in Fig. 1, the network consisting of six nodes is shown in the upper part, and the latent metric space is indicated by