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Information transport in multiplex networks

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HIGHLIGHTS

- We study information transport in multiplex networks.
- We propose an attack centrality measure for multiplex networks.
- Assortative coupling is better than the other coupling strategies in our model.

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ABSTRACT

In this paper, we study information transport in multiplex networks comprised of two coupled subnetworks. The upper subnetwork, called the logical layer, employs the shortest paths protocol to determine the logical paths for packets transmission, while the lower subnetwork acts as the physical layer, in which packets are delivered by the biased random walk mechanism characterized with a parameter α. Through simulation, we obtain the optimal α corresponding to the maximum network lifetime and the maximum number of the arrival packets. Assortative coupling is better than random coupling and disassortative coupling, since it achieves better transmission performance. Generally, the more homogeneous the lower subnetwork is, the better the transmission performance, which is the opposite for the upper subnetwork. Finally, we propose an attack centrality for nodes based on the topological information of both subnetworks, and investigate the transmission performance under targeted attacks. Our work aids in understanding the spread and robustness issues of multiplex networks and provides some clues about the design of more efficient and robust routing architectures in communication systems.

1. Introduction

Communication infrastructures, such as the Internet, mobile phone networks, wireless sensor networks etc., have become increasingly interconnected, forming large growing interdependent communication networks. For example, every day people chat with each other through mobile phone networks, or communicate through the Internet using the communication software, such as email, Facebook, etc. Usually, communication flows through many networks, when the distance between the source and destination is vast. In the battlefield, soldiers and vehicles are connected by different kinds of communication channels (e.g. wireless or not) for reliable communication. In all these systems, nodes are connected by more than one kind of link. Each kind of link forms a single network layer, and network layers are often coupled for specific purposes. In addition to the technological systems, multiple links or interactions among units also widely appear in social

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and biological systems [1]. The multiplexity nature of these systems has attracted considerable attention from research communities in the past few years, and has brought about a new research topic, namely multiplex networks [2,3].

Recently, researchers are focusing on the redefinition of the basic structure measures from a single complex network [4], and are investigating how multiplexity of layered network structures affect the dynamical processes such as epidemic spreading [5–7], percolation [8–10], games [11–13], synchronization [14,15], etc. The transmission of information is a common spreading process on communication networks, which is widely studied in single complex networks [16–23]. The most concerning problem is how to alleviate congestion in order to enhance network capacity. Arenas et al. [24] illustrated phase transition of traffic from the perspective of the critical packet generation rate, which was thereafter used as the indicator of network capacity. Zhao et al. [25] theoretically discussed the network capacity of several traditional topological structures by considering the delivery capacity as well as the betweenness of nodes. Other researchers proposed many hard or soft strategies to improve the network capacity [16]. The hard strategies modify the network structure or optimize the network resource allocation. For example, Liu et al. [26] found that it is effective to improve network performance by deliberately removing a small set of edges among core nodes. Similarly, Zhang et al. [27] found that deleting some edges among high-betweenness nodes will improve the network capacity. Gong et al. [28] obtained that for a given network and a routing strategy, there is an optimal resource allocation scheme corresponding to the maximum network capacity which is inversely proportional to the average length of the routing paths.

The hard strategies are often too expensive or not applicable in real situations. More attention has been paid to the designing of efficient routing strategies [16]. In the representative shortest path protocol, traffic flows are directed to pass by core nodes in order to rapidly reach destinations, but this leads to traffic congestion. Yan et al. [29] proposed an efficient routing strategy, which intentionally avoids traffic flow passing by core nodes and redistributes traffic load from the core nodes to the marginal nodes. This routing strategy greatly improves the network capacity when the delivery capacity of nodes is identical. Danila et al. [30] employed a heuristic algorithm to minimize the maximum node betweenness for improving network capacity. Wang et al. [31] proposed a dynamic routing strategy, which considers both the degrees and loads of neighbor nodes. There are many other efficient routing strategies which consider the waiting time of packets in the queue [32], the distance of the destinations from the neighbor nodes [33,34], and so on.

Until recently, some researchers studied traffic dynamics on multilayer complex networks. Zhuo et al. [35] studied traffic dynamics on two-layer complex networks comprised of a logical layer and a physical layer, and found that the physical layer is more critical to the overall network capacity. Du et al. [36] studied the traffic dynamics on coupled spatial networks with different travel cost among different network layers. Tan et al. [37] investigated the effects of interconnections on traffic congestion in two coupled scale-free networks generated by the Barabási–Albert (BA) model [38]. They found that assortative coupling alleviates traffic congestion better than disassortative coupling and random coupling when node capacity is allocated according to node usage probability. Nian et al. [39] compared several routing strategies on two layer degree-coupled networks. Zhou et al. [40] studied the routing issues on multilayered communication networks comprised of a wired network and a wireless network.

In many communication networks, the nodes have a limited power supply, and do not work when the batteries run out of power. Especially in wireless sensor networks, the nodes have limited delivery capacity, power capacity, storage capacity, and communication distance. The most important part is to make the networks survive as long as possible. Thus, in the power-limited networks, network lifetime [41–43] is more important than network capacity. In this paper, we study the information transmission in multiplex networks comprised of two coupled subnetworks. We focus on network lifetime as well as number of arrival packets from the perspective of coupling strategies, routing protocols, network structures, and network attacks.

2. The network model

In our multiplex networks, there are two network layers. The two network layers have the same number of nodes and the same average node degree. The topological structures of the network layers are generated by network models such as the Erdös and Rényi (ER) model [44] and the static (ST) model [45]. The ER model generates random networks with a Poisson degree distribution. The static model generates scale-free networks with a power-law degree distribution. Nodes in different layers are connected based on one of three rules: random coupling, assortative coupling, and disassortative coupling. For random coupling, nodes in different layers are randomly connected. For assortative coupling, large-degree nodes in one layer are also connected with the large-degree nodes in the other layer. For disassortative coupling, large-degree nodes in one layer are connected with small-degree nodes in the other layer. From another point of view, each node of the multiplex network has two substitutes: one in the upper layer and the other in the lower layer. The two substitutes are connected with an edge.

3. The traffic model

The upper layer in our multiplex network is the logical layer. In this layer, every node generates packets with rate ρ. If ρ is 1.5, then a node will generate one packet and another packet with probability 0.5 each time. The destinations of the packets are randomly selected among other nodes except the source nodes. The routing paths for the packets are calculated