



Dominating complex networks by identifying minimum skeletons



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ABSTRACT

By identifying important nodes (driver nodes), the minimum dominating set (MDS) provides an effective model to dominate complex networks. However, in many networks, the skeleton of driver nodes selected using the MDS is usually connected, which motivates us to explore a new framework and try to dominate a network by identifying its minimum skeleton. We define the minimum skeleton of a graph as a subgraph induced from the nodes within the minimum connected dominating set (MCDS), and the problem can be solved by a maximum spanning tree-based algorithm. For the domination of complex networks, in general, the MCDS needs more driver nodes, and is more robust than the MDS against link attack. Interestingly, for the MDS, it is harder to control the networks with weaker communities, while for the MCDS, this finding tends to be observed on the networks with homogeneous community sizes. In addition, for the MDS, the curves for the percentage of driver nodes on the networks with variable community strengths shift downward as the average degree of the networks increases, while for the MCDS, the curves, like power functions rotate clockwise. For the both, it tends to be harder to control the networks with stronger overlapping, and the number of driver nodes is dependent on the networks' degree distribution.

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1. Introduction

Complex networks have been extensively studied for plenty of years [1,2], which have many applications including transportation [3], communications [4]. This research field can be divided into multiple specific areas, and the network structure analysis such as community detection as one important area of complex networks provides us with a deep insight into understanding the hierarchical structures of network-based systems [5–13] since each community often corresponds to an important unit in the organization. In recent years, network control in complex networks has attracted more attention, and it provides a new way to understand network-based systems [14–20]. Recent works also showed that network structures have great impact on network control [21,22].

Network control is an outstanding challenge for us, and many frameworks have been proposed to study the controllability [14–20] as well as the domination of complex networks [21–28,43]. A dynamic system is controllable if suitable inputs of external signals can activate it in finite time from any initial state to any final state [29–31]. Liu et al. [14] studied the structural control-

ability on directed networks and transformed the problem into the determination of the minimum driver nodes. Driver nodes correspond to unmatched nodes in the maximum matching of the networks, and the full control of the networks can be achieved through driving the unmatched nodes by external signals [14]. The results showed that the networks' degree distribution primarily determines the number of driver nodes, and driver nodes in directed networks tend to avoid high-degree nodes [14]. Remarkably, Nacher and Akutsu [23] introduced the minimum dominating set (MDS) to dominate complex networks, and the results indicated that the structural controllability can be achieved by selecting nodes within the MDS as driver nodes [23,26]. Nacher and Akutsu [23,26] further mentioned that the structural controllability model assumes that external signals can only directly control unmatched nodes (driver nodes), while the MDS-based model assumes that driver nodes can independently control their associated links. Wuchty [27] used the MDS-based model to analyze protein interaction networks, and the results showed that proteins within the MDS often correspond to important nodes, which tend to be essential, disease-related and virus-targeted genes. More information can refer to the review works [15,26].

By identifying important nodes (driver nodes), the MDS provides us with an effective model for the domination of complex networks. However, in many networks, the skeleton of driver nodes selected using the MDS is usually connected. For example, in com-

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munication systems, connected dominating sets are useful for the computation of routing in mobile ad hoc networks [4]. In this application, a minimum connected dominating set (MCDS) is considered as a backbone for communications, and nodes that do not belong to this set communicate by passing messages through their neighbors that belong to the set [4]. Therefore, we take advantage of this, and find dominating sets/driver nodes by looking for the minimum skeletons. We define the minimum skeleton of a graph as a subgraph induced from the nodes within the MCDS, and the problem can be solved by a maximum spanning tree-based algorithm. Further, we analyze the domination of random networks and real-world networks based on the MCDS-based model.

The rest of the paper is organized as follows. In Section 2, we describe some preliminary definitions. In Section 3, we introduce our framework for the domination of complex networks. In Section 4, we present the experimental results on random networks and real-world networks. The conclusion is provided in Section 5.

2. Preliminary definitions

In this section, we describe some preliminary definitions that are helpful for understanding the models of the domination of complex networks. Here, we use $G(V, E)$ to denote an unweighted, undirected graph, where V is the node set, and E is the edge set. $A = (a_{ij})_{n \times n}$ is the adjacency matrix of $G(V, E)$, and $a_{ij} = 1$ indicates that node i and node j are adjacent, and 0 otherwise, where $|V| = n$.

Definition 1 (dominating set). V' is a dominating set (DS) of $G(V, E)$, if $V' \subseteq V$, and $V' \neq \emptyset$, $\forall i \in V - V'$, $\exists j \in V'$, $a_{ij} = 1$, $i \neq j$.

Definition 2 (connected dominating set). V' is a connected dominating set (CDS) of $G(V, E)$, if (1) V' is a dominating set, and (2) the induced subgraph $G'(V', E')$ from $G(V, E)$ by the nodes in V' is connected, where $G(V, E)$ is a connected graph.

Definition 3 (node degree). The degree of a node is defined as the number of nodes that is adjacent to it. Formally, $\deg(i)$ denotes the degree of node i , and $\deg(i) = \sum_{j=1}^n a_{ij}$, where $i, j \in V$.

Definition 4 (spanning tree). A subgraph $G'(V', E')$, is called a spanning tree of $G(V, E)$ if $G'(V', E')$ is a tree, and $V' = V$.

3. Models for dominating complex networks

In this section, we describe the minimum dominating set (MDS)-based model and introduce the minimum connected dominating set (MCDS)-based model.

3.1. MDS-based model

Here, we first discuss the MDS of a network as well as the rationale of the MDS-based model for the domination of complex networks. Then, we determine the MDS by binary integer programming.

A dominating set is called the minimum dominating set (MDS) if no dominating set exists in a given graph with fewer nodes [23–26]. For dominating a network, the MDS-based model tries to identify important nodes, which correspond to the nodes within the network's MDS [23–26]. We can achieve full control of a network if we control all the driver nodes since driver nodes not only can control themselves, but also can control independently each of the outgoing links, i.e., driver nodes are always controllable, and non-driver nodes are controllable if they are adjacent to a driver node at least, where nodes within the MDS are called driver nodes [23–26].

Identifying the MDS of a network can be solved by '0-1' integer programming [23–27],

$$\min \sum_{i \in V} x_i \quad (1)$$

subject to

$$x_i + \sum_{j \in V} a_{ij} x_j \geq 1 \quad (2)$$

where $x_i = 1$ indicates node $i \in \text{MDS}$, and 0 otherwise, $i = 1, 2, \dots, n$.

Here, we use the lpSolve of the R package to solve the linear programming (LP) problem [27], which has been fully discussed by Wuchty [27].

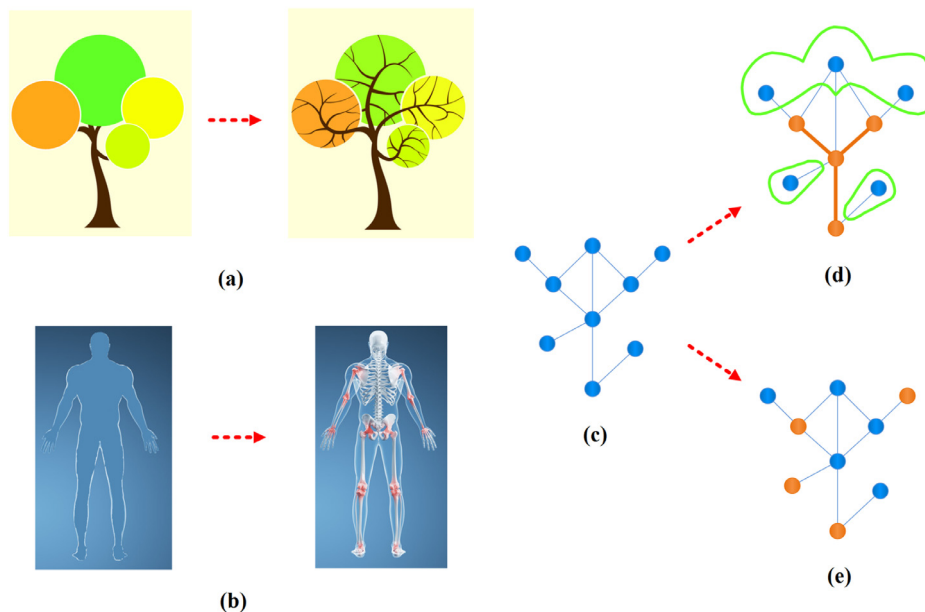


Fig. 1. Illustration of the domination of complex networks. (a) and (b) correspond to a tree and a person respectively. (c) corresponds to a graph. (d) and (e) illustrate the MCDS-based model and the MDS-based model respectively. Driver nodes and non-driver nodes are brown and blue colored respectively. Driver nodes in the minimum skeleton are connected with bold lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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