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An Adaptive Framework for Backbone Extraction Using the Component Structure in Complex Networks

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1 Abstract

This study presents an Adaptive Backbone Extraction Framework designed to address the challenges of network heterogeneity. Unlike traditional methods that apply a uniform approach to the entire network, this framework distinguishes between local, densely connected components and their broader interconnections, termed global components. The framework captures fine-grained and overarching network structures, allowing customized backbone extraction techniques within each component. Experiments on real-world networks demonstrate that this approach preserves critical local and global properties more effectively than classical methods, making it a versatile tool for diverse network applications.

2 Introduction

Backbone extraction is a crucial technique for simplifying large, complex networks by retaining only the most significant connections. This reduction makes it easier to analyze and visualize complex systems. Traditional backbone extraction methods often face challenges in handling networks with inhomogeneous edge weights and densities leading to loss of key information [1–9]. To address this issue, we introduce a Backbone Extraction Framework that leverages the mesoscopic structure of networks [10]. It leverages on the network component structure that have proven to be a flexible mesoscopic representation for network analysis [11–18]. The component structure reflects the nonuniform density of real-world networks, grouping densely connected local components while sparsely connected global components link them. By applying specialized backbone extraction techniques to each component independently, the framework preserves structural features unique to each part of the network. Figure 1 illustrates the multilevel backbone extraction framework, showing the network segmentation into dense local components and sparsely connected global components. Backbone extraction methods are applied within each component, followed by integration into a cohesive backbone structure.

Figure 1 illustrates the process of the proposed multilevel backbone extraction algorithm on a weighted undirected network.

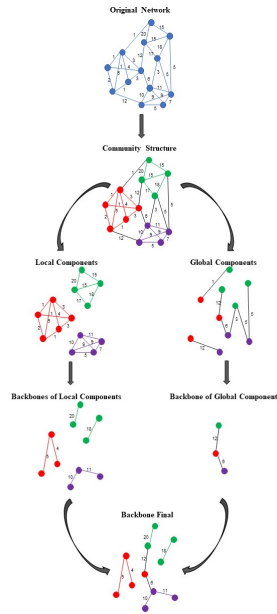


Fig. 1. Multilevel Backbone extraction Framework. A community detection algorithm is applied to the original network to reveal its dense components. In the second graph, colors highlight communities, with intercommunity links in black. To obtain the global components, intracommunity links are removed, as shown in the graph on the right. Conversely, inter-community links are removed to isolate the local components, depicted in the graph on the left. Once the components are uncovered a backbone extraction algorithm is applied to each component to reveal the components backbones. Finally, the multilevel backbone is obtained by merging all the backbones of local and global components.

3 Results

We investigate the effectiveness of the Multilevel Backbone Extraction Framework on a range of real-world networks, from small networks (e.g., Zachary’s karate club) to large, complex networks (e.g., scientific collaboration networks). The evaluation metrics include global properties (e.g., density, clustering coefficient), mesoscopic features (e.g., modularity, participation coefficients), and distance measures to assess how well the extracted backbone preserves the original network structure. These experiments aim to evaluate the advantage of the Multilevel Framework over classical backbone extraction methods in retaining key network properties. In this study, we apply the same primary backbone extraction technique to all components within the framework. However, the framework is designed to allow flexibility in mixing different techniques across individual components. The two primary techniques used are the Global Threshold, which retains edges above a predefined weight threshold, and the Disparity Filter, which applies

a local, node-specific threshold to capture significant connections within heterogeneous components.

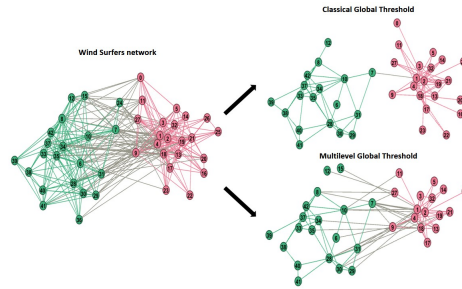


Fig. 2. The extracted backbones using Global Threshold of the 'Wind Surfers' network (43 nodes and 336 edges), with a fraction of edges fixed at 30%.

Global Threshold and Disparity Filter Performance: The Global Threshold method is effective at maintaining large-scale structural properties, preserving the diameter and density of the network backbones, making it particularly suitable for larger networks. In contrast, the disparity filter excels in conserving modular structures and weight distributions, capturing the essential local characteristics within densely connected network components. This method demonstrated advantages in smaller networks where community structures and local connections were crucial to accurate representation of the backbone.

Comparative Findings: Across all tested networks, the multilevel framework outperforms classical single-threshold methods, preserving both local and global properties more consistently. Notably, the Multilevel Global Threshold approach, with its component-based adaptive thresholding, allowed for better retention of the original network's modularity and connectivity patterns. In particular, networks with substantial heterogeneity saw the most significant improvements, as the framework component-based approach successfully captured high-density and sparse areas without compromising connectivity across the network. Figure 2 shows the comparison of the backbones extracted by the multilevel framework versus the classic global threshold method on a sample network, highlighting the improved retention of structural features and connectivity achieved by the multilevel approach.

Implications for Network Analysis: By maintaining both intra and intercommunity connections, the framework provides a more faithful representation of original network structures, which is essential for applications where network functionality and connectivity patterns must be preserved. Future research could expand the framework by integrating more advanced extraction techniques. Furthermore, while the current framework allows flexibility in choosing backbone extraction techniques across components, an extension could involve developing adaptive algorithms that automatically select each component's most suitable extraction method based on its structural properties.

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