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Impact of Diffusion Dynamics on Community-Aware Centrality Measures

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1 Abstract

This work examines the impact of diffusion dynamics on community-aware centrality performance on networks with varying community structures. We extensively analyze the effectiveness of multiple centrality measures in ranking influential nodes by comparing four different network diffusion models (Susceptible-Infected, Susceptible-Infected-Recovered, Linear Threshold, and Independent Cascade models) on synthetic and real-world networks. Results show that the community structure strength, the internal dynamics of the diffusion model, and budget availability are critical to determining the diffusive power of nodes. Simple contagion models (SI, SIR, IC) show very consistent patterns of diffusion, while the complex contagion dynamics provided by the LT model behave quite differently. This study sheds light on selecting the most influential nodes to maximize diffusion in real-world applications in epidemiology, analysis of social networks, and marketing.

2 Introduction

Understanding diffusion processes in networks is critical across disciplines like sociology, biology, and epidemiology, where spreading information, behaviors, or diseases can have significant impacts. Traditional centrality measures, which assess node importance based on network topology, often fail in networks with strong community structures, leading to suboptimal identification of critical nodes. To address this issue, community-aware centrality measures have been developed [1–17]. These measures have demonstrated their effectiveness in identifying influential nodes within community-structured networks, particularly under specific diffusion models like Susceptible-Infected-Recovered (SIR). However, most studies focus narrowly on a single diffusion model or a limited set of network types, limiting their generalizability. Additionally, the effects of different community detection algorithms and network topologies on these measures remain underexplored. This study fills these gaps by systematically evaluating multiple community-aware centrality measures across diverse diffusion models and network structures, providing a comprehensive understanding of how diffusion dynamics interact with network topology to influence the effectiveness of centrality measures [18]. The study focuses on diffusion models originating from epidemiology (Susceptible-Infected (SI), Susceptible-Infected-Recovered (SIR)), and social networks models describing the

spread of information or behaviors (Linear Threshold (LT), and Independent Cascade (IC)). We systematically analyze eight community-aware centrality measures:

1. Participation Coefficient: Measures the extent to which a node's connections are distributed among different communities, emphasizing nodes that link multiple communities.
2. Community-based Centrality: Identifies influential nodes by considering their degree within their community and their connectivity to other communities.
3. Comm Centrality: A measure that adapts to the network's community structure, prioritizing either hub-like or bridge-like nodes based on the structure's strength.
4. K-shell with Community: Combines the k-shell decomposition method with community structure information to identify core nodes within communities.
5. Community Hub-Bridge: Identifies nodes that act as hubs within their communities or bridges between communities.
6. Modularity Vitality (targeting hubs and bridges): Evaluates the importance of a node based on its contribution to the network's modularity, targeting either hubs, bridges, or both.
7. Map Equation Centrality: Based on the map equation, this measure uses information theory to identify influential nodes by considering the flow of information in the network.
8. Community-based Mediator: A measure that uses the entropy of a node's intra-community and inter-community links to identify nodes that can quickly disseminate information.

We consider two types of networks: 1) Synthetic networks generated using the Lancichinetti-Fortunato-Radicchi (LFR) algorithm. It allows controlling the community structure strength, size, and degree distribution. 2) Real-world networks from various domains, including social networks, biological networks, infrastructural networks, and collaboration networks. These models, measures, and networks are systematically evaluated to understand how different diffusion dynamics influence the effectiveness of community-aware centrality measures [19].

3 Results

Results on synthetic networks show that diffusion models (SI, SIR, IC, LT) exhibit distinct behaviors depending on the community structure strength. In simple contagion models (SI, SIR, IC), the diffusion patterns are similar when the community structure strength and budget remain constant. However, the LT model, representing complex contagion dynamics, behaves differently, often requiring a combination of hub-like and bridge-like nodes for effective diffusion. The study reveals that the community size distribution and degree distribution also affect the performance of centrality measures. For instance, networks with a large variance in community sizes or degree distributions exhibit different diffusion dynamics than networks with more homogeneous structures.

In real-world networks, the performance of community-aware centrality measures varies based on the specific network's topological characteristics. The paper categorizes real-world networks into two types: those with strong community structures and those

with medium to weak ones. In networks with strong community structures, bridge-like nodes tend to be more effective, while in networks with weaker structures, the combination of hub-like and bridge-like nodes yields better diffusion results. Bridge-like nodes are more effective in spreading diffusion in networks with strong community structures because they connect different communities, facilitating the spread of information or diseases across the network. Conversely, targeting hub-like nodes becomes more effective in networks with weak community structures, especially when the budget for initial infections/activations is high.

Overall, the effectiveness of community-aware centrality measures in maximizing diffusion is contingent on multiple factors, including the network's community structure strength, the underlying dynamics of the diffusion model, and the budget available for initiating diffusion. The study [19] emphasizes the need for a nuanced approach when selecting centrality measures, as different scenarios may require different strategies for optimal diffusion. The findings offer valuable implications for practitioners, particularly in fields like epidemiology, marketing, and social network analysis, where understanding and controlling diffusion processes are crucial.

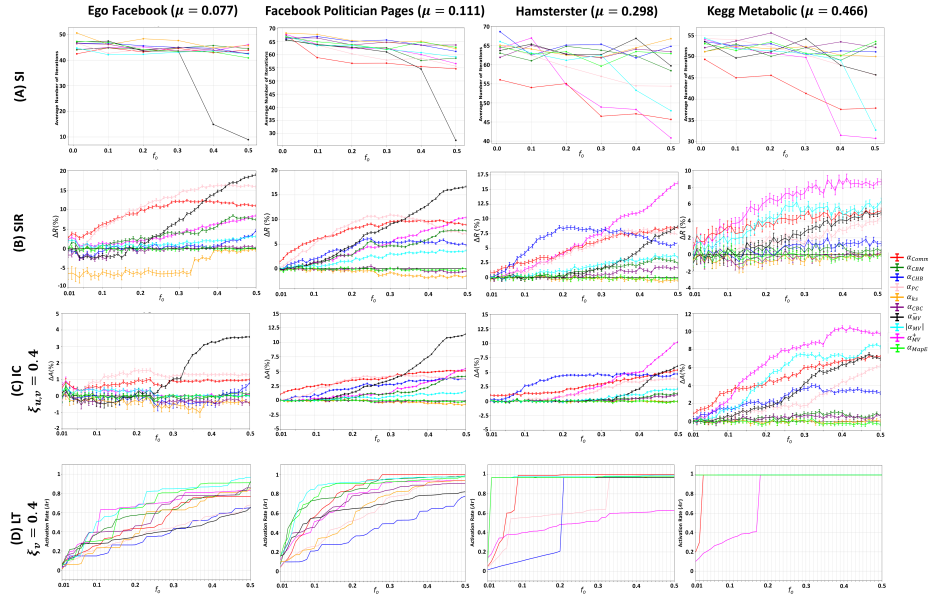


Fig. 1. Performance of the community-aware centrality measures in real-world networks. The first, second, third, and fourth rows indicate the results of the (A) SI model, (B) SIR model, (C) IC model, and (D) LT model, respectively. The y-axis of each model represent the following: (1) SI model - time to infect 50% of the network, (2) SIR model - relative outbreak size, (3) IC model - relative activation size, (4) LT model - normalized number of active nodes. The x-axis for all models, f_o , indicates the fraction of initially infected/activated nodes.

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