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On Diffusion, Community Structure, and Community-aware Centrality in Network

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Abstract: This work examines the interaction between diffusion dynamics, community-aware centrality measures, and network topologies. We evaluate how the diffusive power of nodes, selected based on various community-aware measures, evolves with the diffusion model and the network structure.

This work has applications across various domains, including social network analysis [1-3], disease modeling [4-7], internet structure analysis [8], and infrastructure resilience [9-11]. Challenges include limited studies on multiple-spreader phenomena and insufficient comparison of community-aware centrality measures in diverse networks [12-15]. Previous research focused on a small set of networks, limiting rigorous performance evaluation and bottlenecks. To address these challenges, we simulate four diffusion models: Susceptible-Infected (SI), SIR, Independent Cascade (IC), and Linear Threshold (LT) models, using seed nodes selected based on community-aware measures on synthetic and real-world networks under a multiple-spreader scheme [16].

The community-aware centrality measures under investigation include 8 influential solutions to identify influential nodes in modular networks. We describe them briefly. In 2005, Guimera and Amaral [17] introduced the Participation Coefficient to uncover key metabolites across species in metabolic networks. Zhao et al. [18] proposed Community-based Centrality, which identifies influential nodes that classical centralities (degree, betweenness, and eigenvector) miss in the Susceptible-Infected-Recovered (SIR) model with a single-spreader scheme. Gupta et al. [19] introduced Comm centrality, which identifies hubs and bridges and adapts to the network's community structure strength. Bridges are prioritized in an immunization scenario using the SIR model. Luo et al. [20] combined community structure and hierarchy to develop a K-shell with Community, outperforming classical centrality measures in the SIR model with a single-spreader scheme. Tulu et al. [21] used the entropy of a node's intra-community and inter-community links to identify nodes that disseminate information quickly in the SIR model. Ghalmane et al. [22] proposed a Community Hub-Bridge, which effectively hinders epidemics by immunizing influential nodes in networks with strong community structures under SIR dynamics. Magelinski et al. [23] used modularity to identify hubs and bridges. Their community-aware centrality could dismantle large networks more effectively than other measures in the SIR model. Recently, Blocker et al. [24] demonstrated the value of an information-theoretic community-aware centrality measure based on the map equation in the SIR model (single-spreader) and the Linear Threshold (LT) model (multiple-spreader).

Three main parameters are investigated: diffusion model dynamics, community-aware centrality measures, and network characteristics. Synthetic networks are generated using the Lancichinetti, Fortunato, and Radicchi (LFR) algorithm, varying community structure strength, size distribution, and degree distribution. Real-world networks belong to various domains (i.e., infrastructural, social, acting, biological, and collaborative). They cover a large scale of

community structure strength. We use Infomap and Louvain algorithms for uncovering their community structure.

Figure 1 and 2 illustrates the behavior of the community-aware centrality measures under various dynamic models in synthetic and real-world networks with varying community structure strengths. 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.

Results show that community structure strength and budget significantly impact diffusion spread. SI, SIR, and IC dynamics converge, while LT dynamics diverge based on community structure strength and budget. Community-aware centrality measures are more effective in synthetic networks with strong community structures. In real-world networks with strong community structures, bridges are more effective for SI, SIR, and IC dynamics, regardless of budget.

For LT dynamics, hub-like nodes are more effective with limited or high budgets; with increasing budgets, both hub-like and bridge-like nodes are preferred.

In networks with weak community structures, bridge-like nodes are preferred for SI, SIR, and IC dynamics at low budget. Distant hub-like nodes are preferred at a high budget. For LT dynamics, hub-like nodes are preferred at low budget; more interlinked hub-like nodes are preferred from medium to high budget.

We also analyzed the impact of community detection algorithms. Performance changes with a limited budget in SI, SIR, and IC dynamics, while in LT dynamics, differences are seen with a high budget. Differences at limited budget are due to the SI, SIR, and IC models favoring bridge-like nodes for easier information circulation between communities, unlike the LT model, where well-connected communities may not participate in diffusion.

Extensive experiments highlight the interconnections between diffusion dynamics, initial node positions, network community structure strength, and budget availability. Understanding these factors helps choose suitable measures for effective network diffusion.

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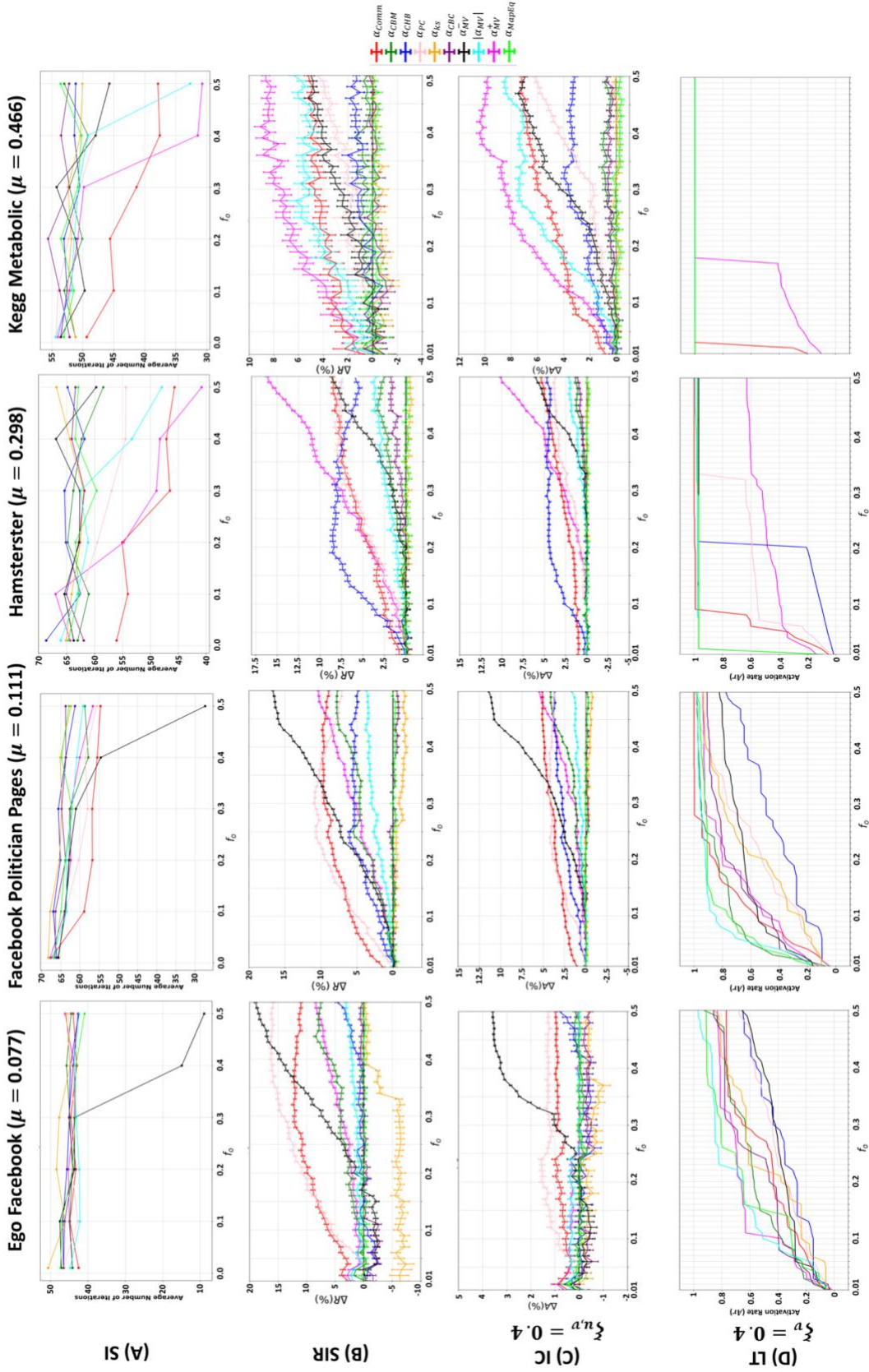


Fig 1. Evolution of the community-aware centrality measures under various dynamic models in real-world networks while varying the mixing parameter (μ). (A) SI model, (B) SIR model, (C) IC model, and (D) LT model

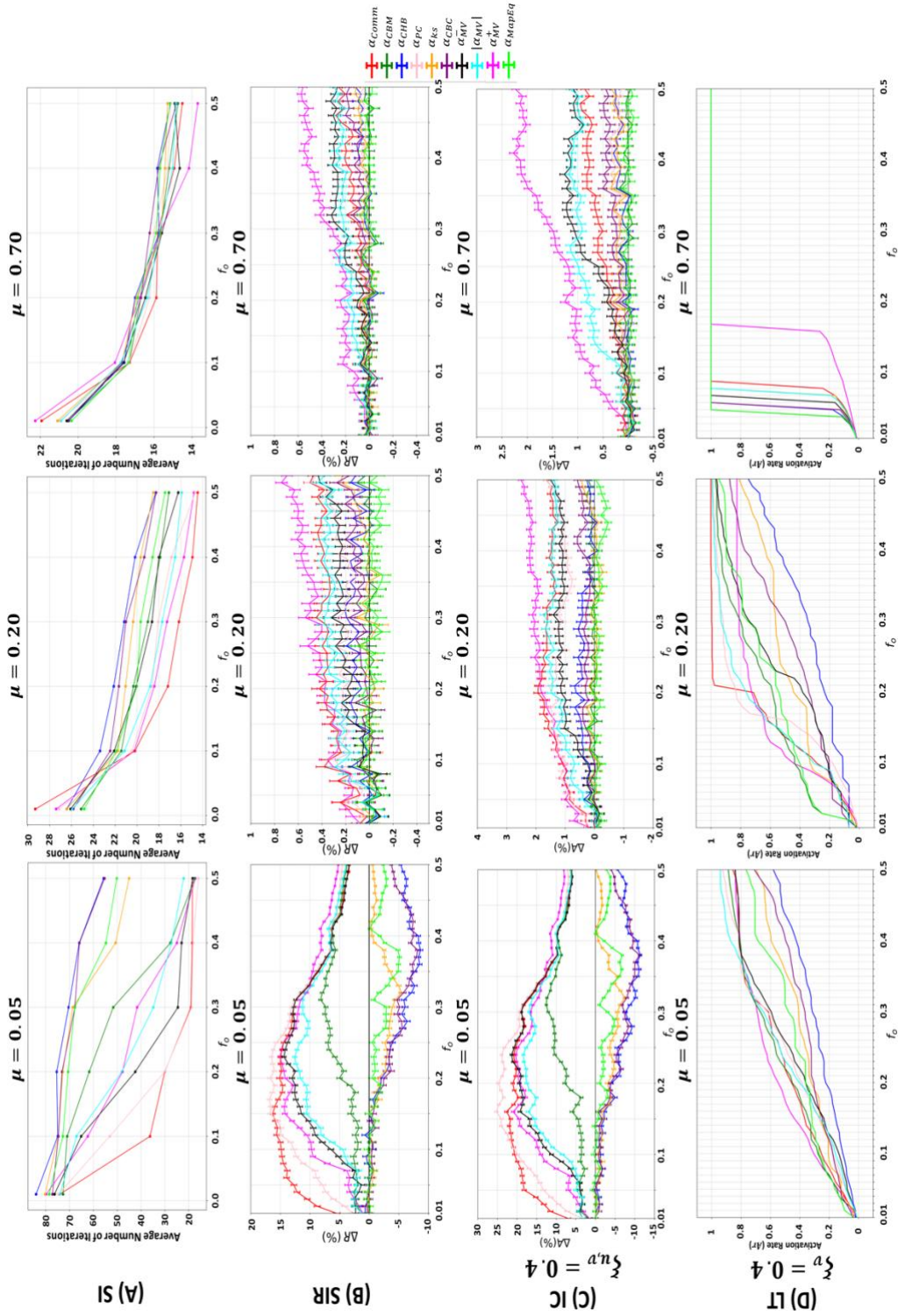


Fig. 2 Evolution of the community-aware centrality measures under various dynamic models in synthetic networks while varying the mixing parameter (μ). (A) SI model, (B) SIR model, (C) IC model, and (D) LT model