Spectral Filtering-Based Anomaly Detection - 25-2-R-11

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Motivation

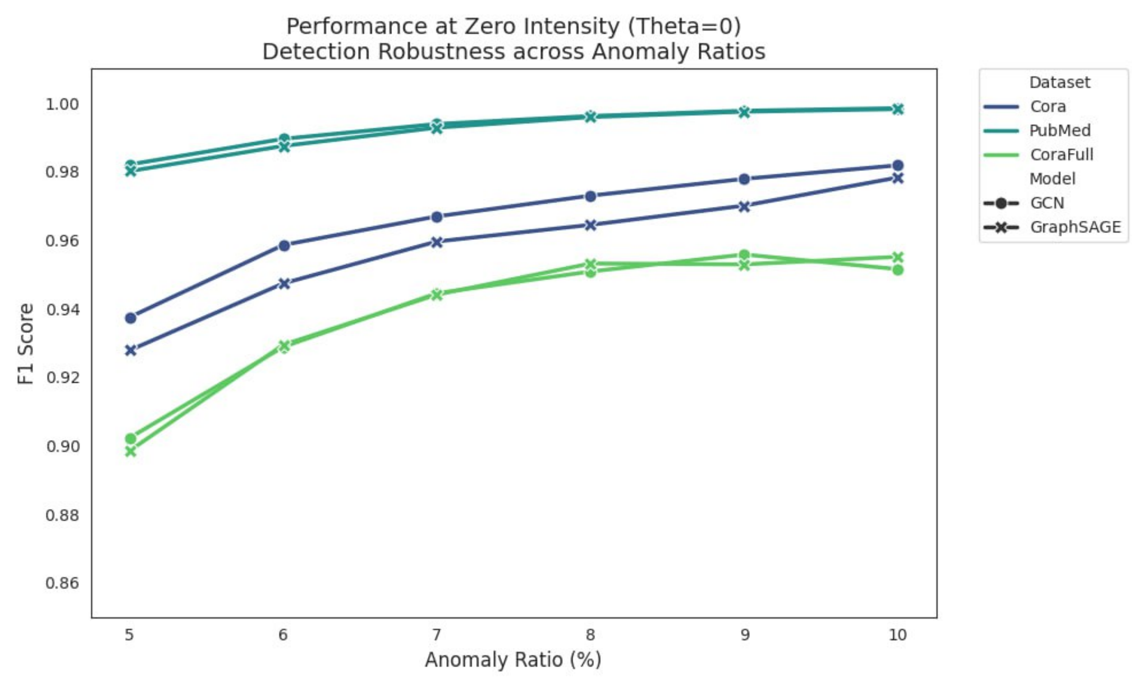
Understanding structural anomalies in graph-based networks is crucial for identifying unusual behaviors, emerging patterns, and data inconsistencies.
Existing anomaly detection approaches rarely consider both **graph attributes and community structure** simultaneously.
This project aims to develop a scalable solution for detecting node-level anomalies in large networks using **spectral graph filtering and community-aware analysis**.

Challenges and Solutions

- **Community Awareness:** Communities are identified via K-Means in embedding space.
- **Correctness:** Injected artificial anomalies to validate the correctness of the detection mechanism.
- **Model Consistency:** Evaluated multiple embeddings to ensure consistent performance.
- **Small deviations:** Anomaly scores are computed from spectral residuals to highlight even small corrections.

Performance and Achievements

- Effective detection of node-level anomalies while **preserving community context** in citation networks.
- **Consistent performance** across GCN and GraphSAGE embeddings, demonstrating robustness to embedding choice.
- The solution is implemented as a **modular framework**, enabling each stage to be independently substituted as required.
- Best performance observed at **anomaly ratios of 5-10%.**
- **Successfully evaluated** on Cora, CoraFull and PubMed datasets.



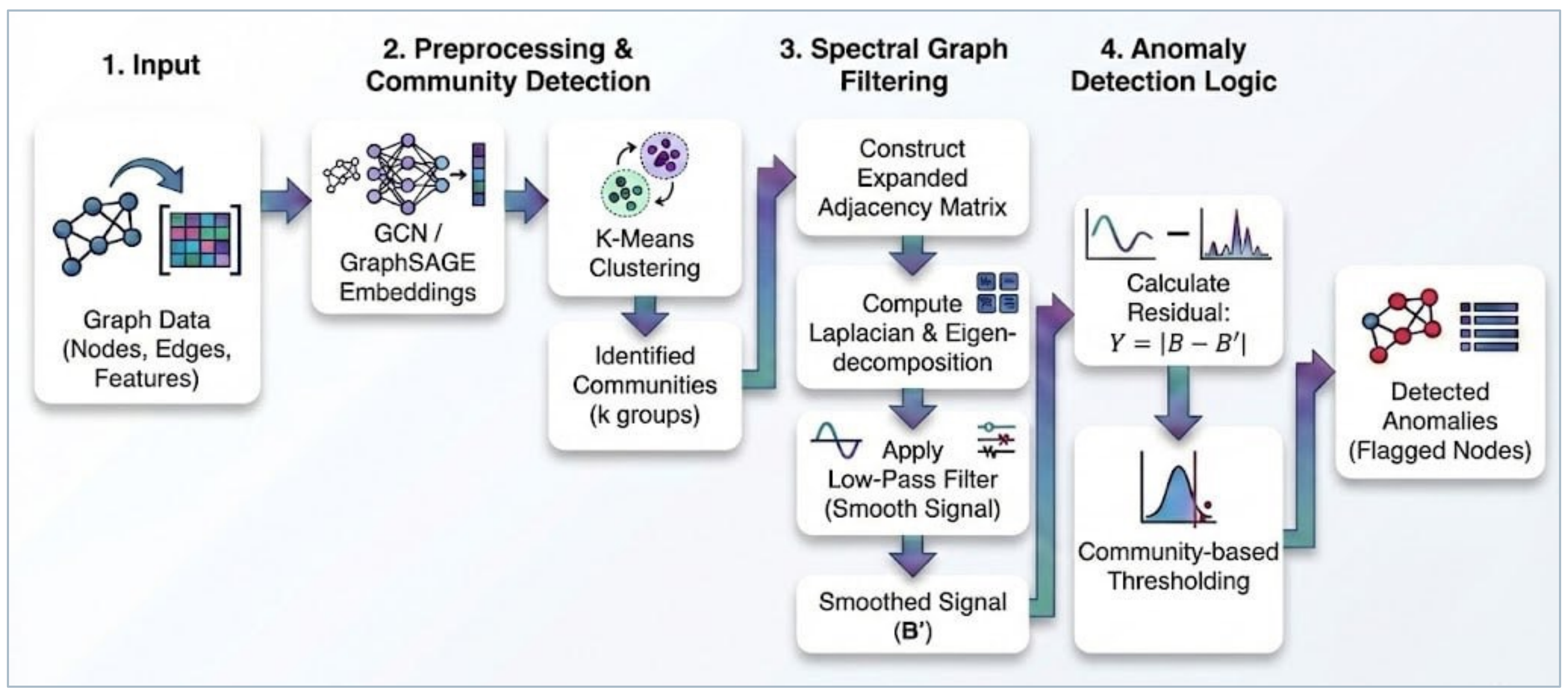
Conclusions

- This solution presents a community-aware anomaly detection framework for citation networks based on a specific **spectral graph filtering**.
- Combining graph embeddings, clustering, and the spectral filtering, enables **effective and interpretable** anomaly detection.
- The framework is **flexible and extensible**, allowing the use of additional embedding models and clustering techniques.
- Community-based thresholding reduces false positives by **tailoring anomaly sensitivity to each community** instead of relying on a single global threshold.
- Community-aware signals preserve local structural context, **enabling the detection of subtle anomalies** that global-only methods often overlook.

Proposed Solution

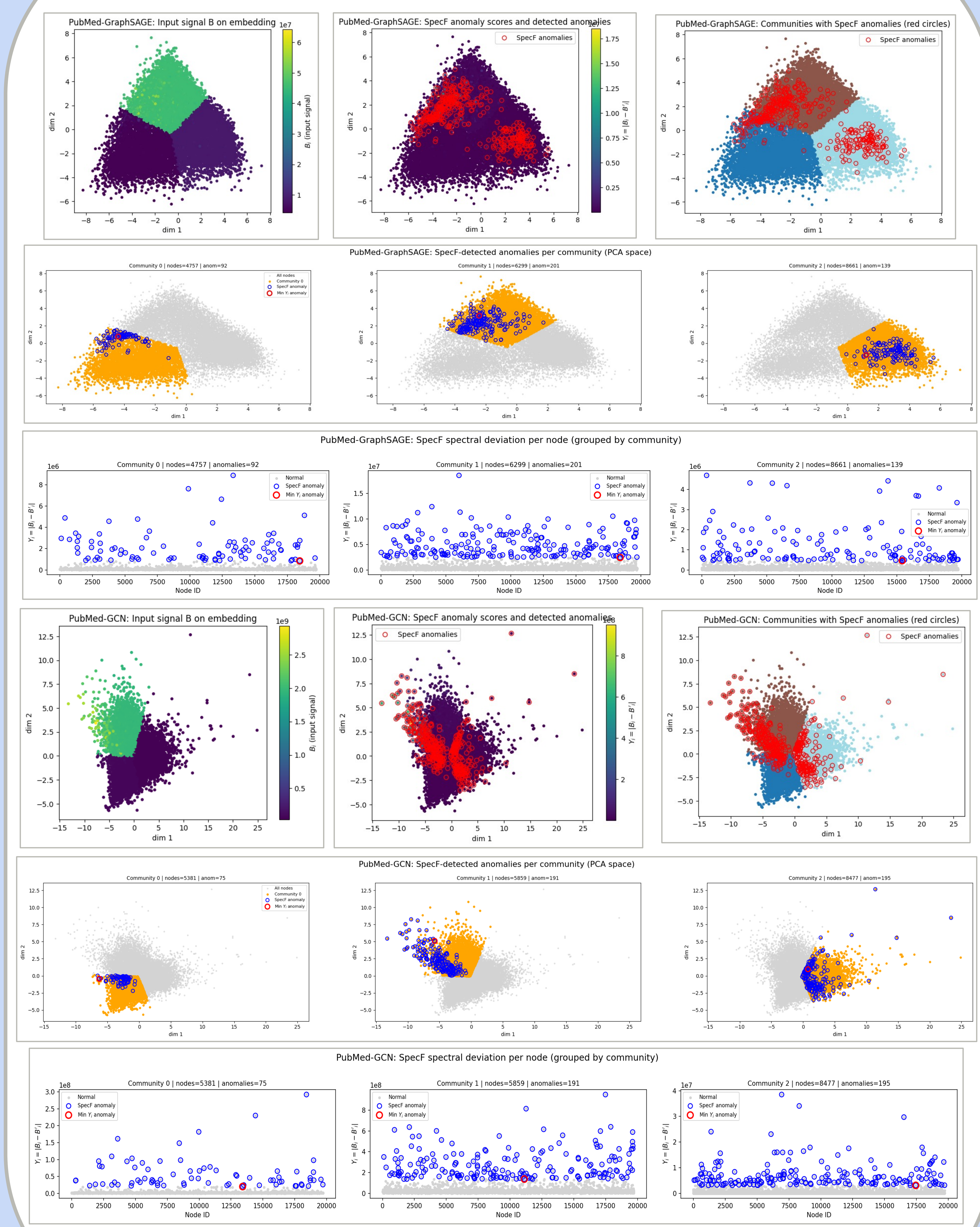
We developed a modular anomaly detection framework consisting of:

- **Graph Embedding:** Node representations generated using GCN or GraphSAGE neural networks.
- **K-Means Clustering:** Communities are identified by clustering nodes in the learned embedding space.
- **Signal Generation:** Signals are generated by propagating community information over the graph to produce smooth values within each community.
- **Spectral Filtering:** Low-pass graph filters used to smooth community-consistent signals and highlight anomalies.
- **Scoring Mechanism:** Node-level anomaly scores defined by the difference between original and spectrally filtered signals.
- **Visualization:** Graph and community-level plots for interpreting anomaly detection results.



PubMed Dataset Results

19717 nodes, 44338 edges, 3 classes, 500 features, GCN + GraphSAGE embeddings



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