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Weighted Community Fusion for Community Detection and Relationship Modelling In Complex Networks

[1]Mrs. M. HEMALATHA, [2]Dr. N. KAMARAJ.

[1]Research Scholar, Department of Computer Science, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore.

[2]Research Supervisor, Assistant Professor, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore.

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Abstract

Community detection is an important step in perceiving network structure and performance for complex network analysis. The rapid growth of network data in recent years has piqued the interest of many researchers in community detection. The majority of community detection methods only consider the network structure. Nonetheless, real-world network nodes may have some characteristics that can be useful for community detection. Most existing optimization-based community detection algorithms are only applicable to disjoint community structure. However, it has been shown that in most real-world networks, a node may belong to multiple communities implying overlapping community structure. Combining multiple community relationship networks (CRNs) is crucial for understanding the holistic interactions among individuals or groups across different platforms or contexts. Existing methods often fail to preserve community structures or handle conflicting edge information effectively. This paper proposes a novel algorithm, Weighted Community Fusion (WCF), which aligns nodes, fuses edges using weighted aggregation, preserves overlapping communities, and iteratively refines the network structure. Experimental results on synthetic and real-world datasets demonstrate that WCF outperforms traditional fusion methods in maintaining community coherence and network connectivity.

1 INTRODUCTION

Community detection is a fundamental problem in the study of complex networks, particularly in social, biological, and technological systems. In a network, a community refers to a group of nodes that are more densely connected internally than with the rest of the network. Detecting such communities helps to reveal the underlying structure, relationships, and functional organization of the network. In community relationship networks, nodes typically represent individuals, organizations, or entities, and edges represent relationships, interactions, or connections among them [1]. These networks can range from online social networks (e.g., Facebook or Twitter) to collaboration networks (e.g., co-authorship in research) and real-world social structures. Understanding the communities within these networks enables insights into patterns such as social circles, influence groups, collaborative clusters, and even potential vulnerabilities. The Community Detection Problem (CDP) is commonly analyzed in different fields, like criminology, public health, social network, and targeted marketing. This problem tried to split the graph into different clusters according to the structure of the graph. Traditional algorithm to solve this problem usually considers the node belongs to a unique community. However, in a physical world network, a node may belong to more than a community. The overlapping nature occurs because of the nodes' different roles played in network systems. The traditional method of finding a community misses the overlapping nature of community, which has sparked increased interest in identifying communities that are overlapping in recent years.

There are many rich and abundant complex networks in the physical world with increased growth concerning communication technology [2]. It leads to the enhancement of the research field complex network analysis to analyze these large networks. The interesting research area in this direction of research is identifying the influential node, monitoring and controlling the network, and

Community detection. A large amount of data and the type of issues that arise concerning complex network investigation receives significant researchers' attention over the last decade. The complex network analysis thus opened many challenges and issues to handle and to produce some appropriate results in the analysis. The most active research in this field is to detect community.

Community detection plays a critical role in analyzing these networks by [3]:

1. Identifying subgroups with similar interests, behaviors, or functions.
2. Understanding network dynamics such as information spread, influence propagation, and resilience.
3. Supporting practical applications like targeted marketing, recommendation systems, and anomaly detection.

Various algorithms exist for community detection, including modularity-based methods, hierarchical clustering, spectral clustering, and probabilistic approaches, each suited to different types of networks and research objectives [4]. Despite significant progress, challenges such as overlapping communities, dynamic networks, and large-scale data continue to drive research in this area.

Community detection has been extensively studied, but existing algorithms often face limitations when applied to modern community relationship networks. As networks become larger, more dynamic, and more complex, there is a need for new algorithms that can address these challenges effectively.

1. Increasing Network Size and Complexity.
2. Overlapping Communities.
3. Dynamic Network Behavior.
4. Heterogeneous Relationships.
5. Resolution Limit Problem.
6. Improved Accuracy and Quality.
7. Handling Uncertain and Noisy Data.
8. Emerging Applications.

New community detection algorithms are required because existing methods often struggle with large-scale networks, overlapping communities, dynamic changes, heterogeneous relationships, and noisy data. Developing advanced algorithms helps achieve higher accuracy, better scalability, and more realistic representation of community structures, making them suitable for modern community relationship networks and their evolving applications [5]. The proposed work introduces, The Weighted Community Fusion (WCF) algorithm is designed to detect communities in complex networks by iteratively merging nodes and communities based on edge weights and connectivity strength.

In this paper, the author propose a representative community detection algorithm for attribute-oriented networks, the WCF algorithm, it is particularly useful for networks where relationships are weighted, representing strength, frequency, or significance of interactions. The WCF algorithm aims to: 1) Detect communities that are densely connected internally. 2) Incorporate edge weights to prioritize stronger relationships. 3) Handle both small and large networks efficiently. It’s widely applied in social networks, collaboration networks, and other community relationship networks, where the intensity of interactions matters.

2. RELATED WORK

The detection of communities becomes an important component of complex network research since it leads to the identification of numerous insights in the complex network. The discoveries might be on the characteristics, topology, operations, or behavior of complex networks. Several studies have been conducted in this area to discover algorithms and solutions for community detecting problems [12]. Simultaneously, as the information era progresses, the community detection problem becomes increasingly difficult for researchers. The problem becomes even more difficult to address due to the changing nature and overlapping membership of nodes in a complex network. Identification of community structure is a significant characteristic of a complex network for understanding behavior of a network. It is applicable in several disciplines. The researchers proposed various types of community detection methods.

Pourabbasi, E., et al, (2021), address the problem of community detection in complex networks [6]. The authors proposed a novel single-chromosome evolutionary algorithm with a distinctive architecture modification operator for community detection in complex networks using a combination of structural and content information. A novel virtual network was created by taking into account the structure and content of nodes, and communities were discovered for this network by optimizing the objective function (and using the combinatorial adjacency matrix instead of the structural adjacency matrix) in a series of steps. The proposed algorithm also included a method for sorting new nodes in order to determine the analysis order of nodes along with the local improvement of solution, as well as a new criterion, CS, for measuring the content similarity of nodes. The proposed algorithm was evaluated in real-networks and compared to various state-of-the-art and widely used methods. The Friedman rank algorithm was then used to rank the proposed algorithm and the existing methods using six real networks.

Rahimi, S., et al., (2018), analyse the problem of community detection in complex network [7]. Most of the algorithms developed for this purpose take advantage of single-objective optimization methods which may be ineffective for complex networks. In this article, a novel multi-objective community detection method based on a modified version of particle swarm optimization, named MOPSO-Net is proposed. Kernel k-means (KKM) and ratio cut (RC) are employed as objective criteria to be minimized. Our innovation in PSO algorithm is changing the moving strategy of particles. Experiments on synthetic and real-world networks confirm a significant improvement in terms of normalized mutual information (NMI) and modularity in comparison with recent similar approaches.

Li, Z., & Liu, J., et al., (2016), aimed to carry out in community detection for discovering the community structure hidden in complex networks, and modularity Q is one of the best known quality functions measuring the quality of communities of networks [8]. The authors proposed, a multi-agent genetic algorithm, named as MAGA-Net, is proposed to optimize modularity value for the community detection. An agent, coded by a division of a network, represents a candidate solution. All agents live in a lattice-like environment, with each agent fixed on a lattice point. A series of operators are designed, namely split and merging based neighborhood competition operator, hybrid neighborhood crossover, adaptive mutation and self-learning operator, to increase modularity value. In the experiments, the performance of MAGA-Net is validated on both well-known real-world benchmark networks and large-scale synthetic LFR networks with 5000 nodes. The systematic comparisons with GA-Net and Meme-Net show that MAGA-Net outperforms these two algorithms, and can detect communities with high speed, accuracy and stability.

Yuxin, Z.., et al., (2017), deals the Community structure is an important topological property of complex networks, which has great significance for understanding the function and organization of networks [9]. The authors proposed propose a multi-objective evolutionary algorithm for identifying overlapping community structure in complex networks based on the framework of non-dominated sorting genetic algorithm. Two negatively correlated evaluation metrics of community structure, termed as negative fitness sum and unfitness sum, are adopted as the optimization objectives. In our algorithm, link-based adjacency representation of overlapping community structure and a population initialization method based on local expansion are proposed. Extensive experimental results on both synthetic and real-world networks demonstrate that the proposed algorithm is effective and promising in detecting overlapping community structure in complex networks.

Madadyar, M., et al., (2025), aimed to study and validate Conventional approaches often struggle with computational overhead and limited robustness when addressing large-scale networks or overlapping community structures [10]. The authors present an advanced hybrid meta-heuristic framework that synergistically combines the whale optimization algorithm, salp swarm algorithm, and a novel cloud optimization (CO) algorithm. A modified choice function hyperheuristic is introduced to adaptively orchestrate the optimization process, optimizing the trade-off between exploration and exploitation while maintaining computational efficiency. The CO component, inspired by atmospheric particle dynamics, enhances population diversity and mitigates premature convergence, enabling the framework to effectively capture intricate network topologies. Experimental evaluations were conducted on nine real-world datasets and synthetic Lancichinetti–Fortunato–Radicchi benchmarks, with performance accessed via normalized mutual information and modularity metrics.

Bello-Orgaz, G., et al., (2018), finds the problem of the community detection [11]. The authors proposed new Multi-Objective Genetic Algorithm (MOGA-OCD) designed to detect overlapping communities, by using measures related to the network connectivity [11]. For this purpose, the proposed algorithm uses a phenotype-type encoding based on the edge information, and a new fitness function focused on optimizing two classical objectives in CDP: the first one is used to maximize the internal connectivity of the communities, whereas the second one is used to minimize the external connections to the rest of the graph. To select the most appropriate metrics for these objectives, a comparative assessment of several connectivity metrics has been carried out using real-world networks. Finally, the algorithm has been evaluated against other well-known algorithms from the state of the art in CDP.

The above shortfalls were discovered through a review of the literature. This research focuses on resolving the aforementioned shortcomings to some extent, as detailed in the following chapters. As a result, the research aims to fill a gap in the literature by addressing the overlapping community detection problem in complex networks.

3. PROPOSED METHODOLOGY

Community Relationship Networks (CRNs) represent interactions among entities such as individuals, organizations, or systems [13]. With the growth of online platforms and distributed data sources, multiple CRNs are often generated independently, creating the need for effective network integration techniques.

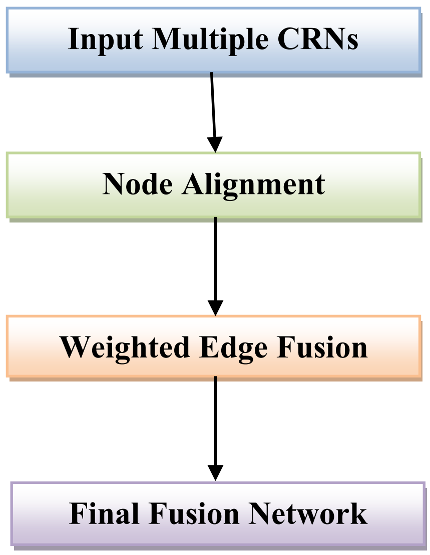

Fig. 3.1: - Workflow of the Proposed Methodology

This paper introduces a novel Weighted Community Fusion (WCF) algorithm designed to combine multiple CRNs while preserving structural and community-level information. The proposed method improves network coherence, reduces information loss, and enhances the quality of the fused network. The proposed WCF algorithm performs node alignment across heterogeneous networks, integrates edge information through a weighted aggregation strategy, preserves overlapping community structures, and iteratively refines the fused network topology to enhance structural consistency. Unlike conventional fusion approaches, WCF emphasizes community coherence while maintaining global network connectivity and minimizing information loss.

Traditional graph fusion methods mainly focus on edge merging and structural simplification. However, these approaches frequently ignore community preservation and fail to address conflicting relationships among networks [14]. Preserving overlapping communities is particularly important because real-world entities often belong to multiple social or functional groups simultaneously.

3.1. Overview

The WCF algorithm combines multiple CRNs through four major phases:

1. Node Alignment
2. Weighted Edge Fusion
3. Community Preservation
4. Iterative Network Refinement

3.2. Node Alignment

Let:

$G_i = (V_i, E_i)$

represent the i^{th} network.

The unified node set is defined as:

$$V = \bigcup_{i=1}^{n} V_i$$

Node similarity is computed using attribute matching and structural similarity measures.

3.3. Weighted Edge Aggregation

For two nodes u and v, the fused edge weight is:

$$W(u,v) = \sum_{i=1}^{n} \alpha_i \cdot w_i(u,v)$$

Where:

- α_i = importance weight of network i
- $w_i(u,v)$ = edge weight between u and v

This weighted strategy reduces conflicting edge effects and improves structural reliability.

3.4. Community Preservation

Communities are detected using modularity optimization.

The modularity score is:

$$Q = \frac{1}{2m} \sum_{u,v} \left[A_{uv} - \frac{k_u k_v}{2m} \right] \delta(c_u,c_v)$$

Where:

- A_{uv} = adjacency matrix
- k_u = degree of node u
- m = total number of edges
- $\delta(c_u,c_v)$ = 1 if nodes belong to same community

Overlapping communities are preserved during fusion.

3.5. Iterative Refinement

The network is refined iteratively by:

1. removing weak edges,
2. strengthening intra-community links,
3. Minimizing disconnected sub graphs.

The refinement stops when modularity improvement becomes negligible.

4. PERFORMANCE ANALYSIS

The experiments to test the performance of WCF algorithm are done on synthetic networks with different parameter settings and on two benchmark real-world networks [15]. The algorithm efficiency is compared with four states of the art algorithm. The experiments are conducted on a system with Intel Core i5-4210U-2.40 GHz, 8 GB RAM, and a 64 bit Windows 7 Operating system. The algorithms are implemented using Matlab R2017b. The EWC_MOEA framework is investigated in both synthetic and real-world networks. Extended Modularity and Generalized Normal Mutual Information are the performance metrics used to assess the algorithms' accuracy and efficiency. Extended Modularity is used in real-world networks where the community structure is unspecified at the outset.

4.1. Experimental Results

4.1.1. Modularity

Modularity is a widely used metric for evaluating the quality of community structures detected in a network. It measures the strength of division of a network into communities by comparing the density of links within communities against the density expected in a random network.

S. No.	Existing Methodology	Modularity
1.	Union Fusion	0.61
2.	Average Fusion	0.68
3.	Proposed WCF	0.84

Table 4.1: - Comparison table of Madularity

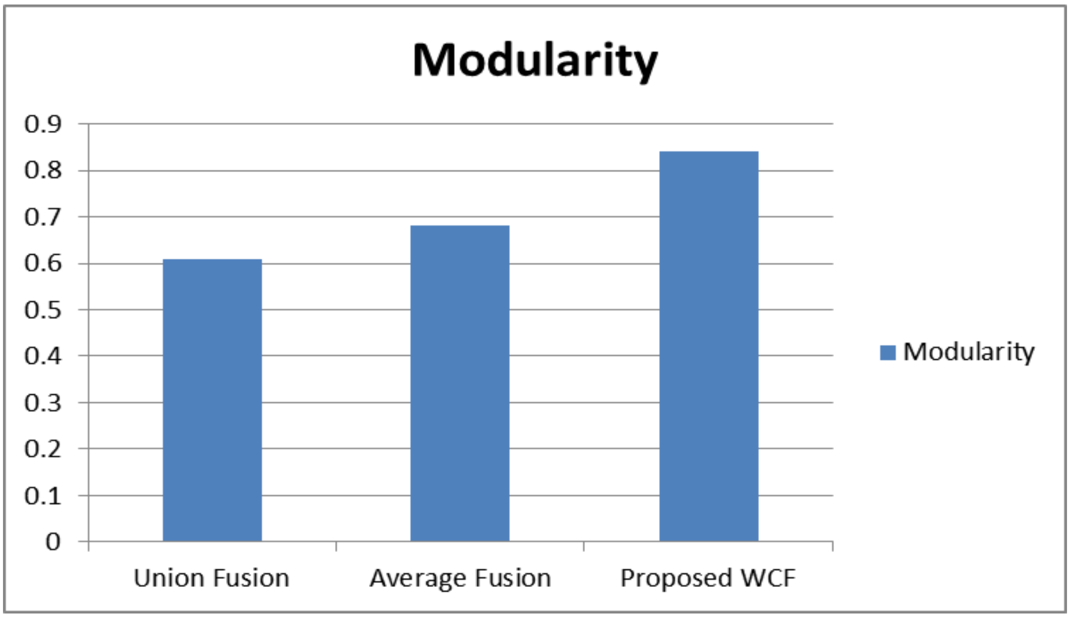

Figure 4.1. Comparison chart for Modularity

4.1.2. Connectivity

Connectivity measures the degree of cohesiveness within a community. It evaluates how well the nodes inside a community are connected to each other, which reflects the strength and robustness of the community structure.

S. No.	Existing Methodology	Connectivity
1.	Union Fusion	0.72
2.	Average Fusion	0.78
3.	Proposed WCF	0.91

Table 4.2: - Comparison table of Connectivity

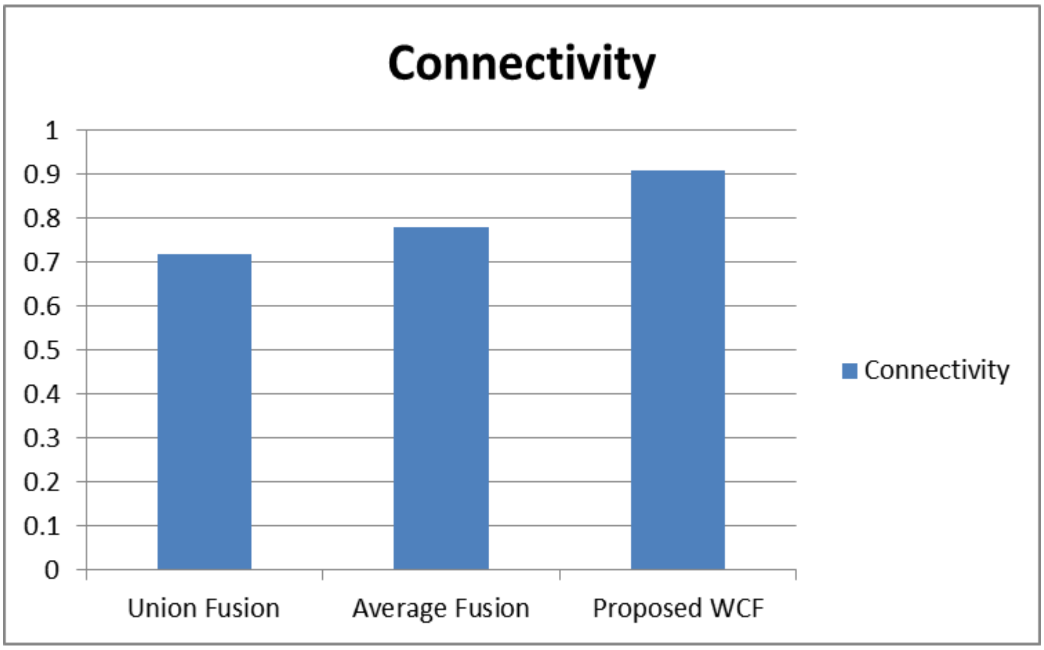

Figure 4.2: - Comparison chart for Connectivity

Experimental evaluations conducted on both synthetic and real-world datasets demonstrate that the proposed method significantly outperforms existing fusion techniques in terms of community preservation, modularity, and structural accuracy. The results indicate that WCF provides an effective and scalable framework for multi-network integration in social network analysis, collaborative systems, and large-scale relational data applications.

5. CONCLUSION

In this work, we propose a methodology to enhance the performance of any community detection technique by providing more informative inputs, resulting in more realistic outcomes. Community detection is of great significance in studying the characteristics of network structure, analyzing user relations, exploring the way of message dissemination and mastering the trend of public opinion. The proposed work implements enhanced algorithm for community detection for large scale networks. The performance of the proposed algorithm is better than other existing ant colony based algorithms.

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