Dynamic Spectral Federated Graph-Level Clustering

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Abstract

Federated graph clustering (FGC) aims to partition distributed graphs into different groups while preserving data privacy. Existing FGC methods focus on spatial-domain information aggregation, while how to use expressive spectral-domain signals of graphs for FGC still remains unexplored. Main challenges are twofold: (1) Collecting and integrating semantic signals that fully express the critical patterns of graphs; (2) Obtaining spectral consensus while preserving local properties of clients. To address these challenges, we propose dynamic spectral federated graph-level clustering (DySFGC). DySFGC designs learnable polynomial filters to capture abundant graph signals and employs spectral contrastive learning and reconstruction to explore the latent semantic information. Besides, DySFGC develops dynamic spectral consensus, which updates the consensus via frequency-specific channels and conducts the dynamic updating process by evaluating the discrepancies between the server and clients. Extensive experiments on fifteen datasets demonstrate the superiority of DySFGC over eleven baselines.

1 Introduction

Graph-level clustering aims to partition graphs into different groups by modeling discriminative graph representations, which is a fundamental task in graph machine learning and has been widely applied to many areas [1, 2, 3, 4]. Existing graph clustering methods mainly follow a centralized learning setting in which all graph samples are unconditionally accessible [5, 6, 7, 8]. However, in real-world applications, such as E-commerce networks [9, 10, 11], cyber-security [12, 13], and intelligent transportation [14], graph data is often gathered from different edge devices with the limitation of privacy requirements, data ownership, and communication constraints, instead of following centralized distribution.

To conquer this issue, federated graph clustering (FGC) has emerged. The FGC learning paradigm is composed of several distributed clients and an independent server. Each client performs local representation encoding and clustering on its own graph dataset while keeping the private graph data in each client unshared. Typically, the server will derive a consensus parameter setting by integrating the parameters uploaded from each client, and then feed back the consensus to each client to update their local parameters. Recent research [15, 16, 17] exhibits productive progress in FGC, which usually leverages spatial-domain encoding integrated with distribution learning to group the graph samples into different clusters. Despite their promising achievements, these approaches overlook the extraction and propagation of graph spectral signals within the graph topology. Spectral signals indicate the diffusion process of graph signal under complex topologies across different frequency

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spectra, which contains rich semantic information and improves the identification of discriminative behavioral patterns [18, 19, 20, 21].

To fulfill this gap, there are two key challenges to be solved. First, although spectral graph learning has been widely studied, it shows incompetence under the FGC scenario. Specifically, the inaccessibility of label information in the unsupervised clustering deteriorates the difficulties of modeling expressive spectral graph signals that contain distinct category characteristics. Therefore, a natural question is posed: **(1) How can we collect discriminative semantic signals from the spectral domain and establish critical spectral patterns of graphs?** Second, it is difficult to model the consensus from the spectral domain since the graph signals with different frequencies may exhibit inconsistent spectral characteristics across clients, which may lead to the cross-client and cross-frequency distribution drift phenomenon during the signal diffusion process. This limitation impedes effective collaborative interactions among clients. Thus, a critical issue exists: **(2) How can we model the spectral consensus and balance it with private properties in distributed clients?** For the first challenge, we develop learnable polynomial filters to extract multi-frequency signals and design exclusive spectral objectives to enhance the discrimination of signals. For the second challenge, we design a novel dynamic spectral consensus module based on multi-level frequencies to capture more generalized consensus across different clients while preserving the private properties.

Based on the above analysis, we propose dynamic spectral federated graph-level clustering (DySFGC). The core of DySFGC is to explore rich spectral signals and dynamically execute frequency-specific parameter updating. Specifically, within each client, we design learnable Chebyshev polynomial filters to capture multi-frequency signals. To obtain more spectral semantics, we employ band-pass reconstruction and spectral contrastive learning to explore discriminative latent representation spaces for clustering. To capture the spectral consensus, we introduce a multi-channel updating mechanism and a dynamic updating mechanism to achieve adaptive interactions between clients and the server.

- **New research task:** To the best of our knowledge, we make the first attempt to tackle the spectral FGC problem, which develops powerful graph filters to capture multi-frequency graph signals and a novel semantic-aware contrastive learning to improve spectral clustering.
- **Novel FGC framework:** A dynamic spectral federated graph-level clustering (DySFGC) framework is proposed to address federated settings, which introduces a multi-channel updating mechanism for spectral consensus generation and introduces a client updating process integrated with traditional server updating.
- **Advanced performance:** Extensive experiments on fifteen graph datasets with five domains demonstrate the superiority of the proposed FedNCN over eleven state-of-the-art baselines.

2 Related Work

2.1 Graph-Level Clustering

In recent years, graph-level clustering has emerged as a dominant paradigm for grouping graph-structured data by jointly learning global representations and clustering assignments in an unsupervised manner. Prevalent solutions prefer to utilize reconstruction to capture the semantics in the graph. For example, SGEC [22] enhances the clustering robustness by reconstructing topological similarity. DBGCN [8] solves the noise problem in graph-level clustering by evaluating the contribution of global representations and measuring the similarity between graphs. Besides, some studies introduce contrastive learning into graph-level clustering to amplify the perception of consistencies among graphs. For example, AMGC [23] introduces adaptive mask strategies to avoid the noise interference and improve clustering robustness. SC-CGC [24] captures the consistencies of graphs via changing the neighbors with different hop numbers. In addition, a couple of approaches focus on multi-view graph clustering [25, 26, 27, 28], which can handle complex graphs with multiple relations. However, most graph-level clustering methods follow centralized learning paradigms, where graph data are unconditionally accessible, and the learning process can be completed by training a single model. This inevitably requires a high degree of data sharing and poses a risk of data leakage. To solve this limitation, we study FGC, which improves the clustering performance of each client by facilitating integration and interaction between model parameters while maintaining high-level data privacy.

2.2 Federated Graph Learning

Federated graph learning (FGL) enables distributed training across diverse clients with graph-structured data, which has broad research and application prospects [29]. The critical step is to achieve communication between clients and the server to jointly model consensus among distributed graph data. For example, FedVN [30] introduces the concept of virtual nodes to moderate distribution shifts across clients. FedGM [31] leverages graph condensation to extract global consensus from clients with different distributions. EaDA [32] extracts latent environmental information by deploying prototype learning and introduces local-global alignment to alleviate distribution shifts. FedIIH [33] explores the influence of intrinsic heterogeneity within clients on global consensus by hierarchical variational inference. S2FGL [34] explores the spectral semantics knowledge based on Laplacian eigenvectors, but it studies traditional graph learning tasks and relies on supervised signals. Recently, traditional supervised FGL has been extended to unsupervised graph clustering [35, 15]. For example, FedGCN [16] introduces topology-oriented feature encoding and prototype consensus optimization for FGC. [17] studies attribute-missing FGC by introducing. However, they only focus on the spatial information propagation and overlook the critical spectral graph signals that contain redundant semantic information about graph data.

3 Preliminaries

3.1 Notations

Consider a client set $\mathcal{C} = \{C_1, C_2, \cdots C_M\}$, where M is the number of clients. In FGC setting, each client C_m holds a private graph dataset $\mathcal{G}^m = \{\mathcal{G}_1^m, \mathcal{G}_2^m, \cdots \mathcal{G}_{N_m}^m\}$, where $N_m = |\mathcal{G}^m|$ is the number of graph samples. Denote $\mathcal{G}_i^m = \{\mathbf{X}_i^m, \mathbf{A}_i^m\}$ as i-th graph in client C_m. $\mathbf{X}_i \in \mathbb{R}^{B_i \times F}$ and $\mathbf{A}_i \in \{0,1\}^{B_i \times B_i}$, respectively, represent the node feature matrix and adjacency matrix, where B_i and F are respectively denote the number of nodes in $\mathcal{G}_i^m$ and the original feature dimension. We denote $\mathbf{Z}_o^m \in \mathbb{R}^{N_m \times F} = \{\mathbf{z}_1, \cdots, \mathbf{z}_{N_m}\}$ as the global representation of graphs in $\mathcal{G}^m$, where $\mathbf{z}_i$ is the global representation of $\mathcal{G}_i^m$. Owing to privacy constraints and non-IID characteristics, clients are not allowed to share graph data [36]. For each client C_m, we define a model f_{θ_m} with learnable parameters θ_m to encode the graph representations. The aim of FGC is to group the $\mathcal{G}^m$ in the client C_m into different clusters $\mathcal{P}^m = \{\mathcal{P}_1^m, \cdots, \mathcal{P}_T^m\}$ and $\sum_i^T |\mathcal{P}_i^m| = N_m$, where T is the the number of graph class. Without loss of generality, we omit the subscripts i and m.

3.2 Spectral Graph Filter

For a graph $\mathcal{G} = \{\mathbf{X}, \mathbf{A}\}$, given the normalized graph Laplacian matrix $\tilde{\mathbf{L}} = \mathbf{I} - \tilde{\mathbf{A}}$, where $\tilde{\mathbf{A}}$ is the normalized adjacency matrix and $\mathbf{I}$ is the identity matrix. $\tilde{\mathbf{L}} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^\top$, where $\mathbf{\Lambda} = \mathrm{diag}(\lambda_0, \cdots, \lambda_{B-1})$ is the diagonal matrix of eigenvalues and $\mathbf{U}$ is eigenvector matrix. Graph filtering function can be defined using K-order polynomial approximation as $g(\mathbf{\Lambda}) = \sum_k^K \omega_k \mathbf{L}_k$ for efficiency. Chebyshev polynomials is one of the most popular schemes [37], which can be defined as: $\Phi_K(\mathbf{L}) = \sum_k^K \omega_k \Gamma_k(\mathbf{L})$, where $\omega_k = \frac{1}{K+1}\sum_{j=0}^K \gamma_j \Gamma_k(\cos(\frac{j+1/2}{K+1}\pi))$ and γ_j is learnable parameters.

4 Methodology

The framework of DySFGC is shown in Fig. 1. In each client, DySFGC employs learnable spectral filters based on Chebyshev polynomials to capture low- and high-pass signals, and implement contrastive learning and reconstruction to exploit rich semantic information. For graph clustering, DySFGC utilizes the KL divergence to evaluate the similarity between the target distribution and the soft clustering distribution. In the server, DySFGC employs a multi-channel updating mechanism, which individually updates the parameters of corresponding learnable modules for high-, low-, and band-pass signals. Besides, DySFGC introduces a dynamic updating mechanism, which captures the spectral consensus while maintaining client-specific properties.

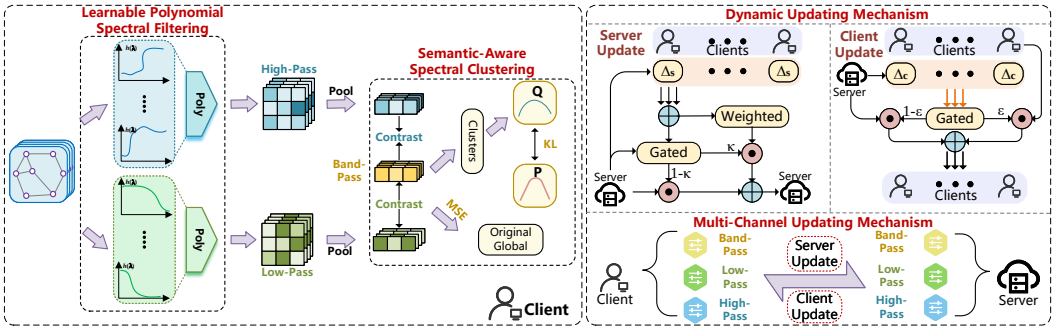


Figure 1: The framework of DySFGC is comprised of three components: learnable polynomial spectral filtering that designs spectral graph filters with learnable parameters based in Chebyshev polynomials to extract redundant high- and low-pass signals, semantic-aware spectral clustering that employs reconstruction and contrastive learning to learn discriminative spectral representations, and dynamic updating mechanism that designs multi-channel updating mechanism for frequency-aware parameters and utilizes the discrepancies between the server and clients to evaluate the weighted contributions of updating parameters. Three parts assemble into a unified framework.

4.1 Learnable Polynomial Spectral Filtering

The spectral domain contains redundant semantic signals that are highly related to the graph patterns. However, traditional graph spectral learning fails to exhibit competence in the unsupervised FGC scene since they lack semantic information about specific frequencies and is usually optimized towards convergence based on supervised label information. To obtain more discriminative spectral representations for clustering, we utilize Chebyshev polynomials [37] with learnable parameters as filter basis to capture low- and high-pass signals with significant semantic information about different frequencies. Wherein, low-pass signals mainly indicate the smoothing similarity between nodes, while high-pass signals help to reveal noise and edge information in the graph. Specifically, the low- and high-pass filters, Φ_K^L and Φ_K^H, can be represented as:

$$\Phi_K^L(\mathbf{L}) = \sum_k^K \omega_k^L \Gamma_k(\mathbf{L}), \Phi_K^H(\mathbf{L}) = \sum_k^K \omega_k^H \Gamma_k(\mathbf{L}). \tag{1}$$

As for the learnable parameter ω_k, DySFGC adopts a sliding Gaussian-parametric-based formulation to achieve the learnable filtering ability:

$$\gamma_j^L = 1 + \sum_{j=0}^K \exp(-\frac{\cos(j)}{2\sigma^2}), \gamma_j^H = 1 - \sum_{j=0}^K \exp(-\frac{\cos(j)}{2\sigma^2}). \tag{2}$$

where σ is a learnable parameter and are respectively initialized to 1. In the Gaussian-parametric model, DySFGC defaults the mean to 0 and leverages the cosine function to limit the sliding parameter j within [-1, 1] to control the filtering intensity. The exponential function ensures the monotonicity of the low- and high-pass filters. Due to $\exp(\cdot) \in (0, +\infty)$, $\gamma_0^L < \cdots < \gamma_K^L$ and $\gamma_0^H < \cdots < \gamma_K^H$, achieving low- and high-pass properties.

Formally, for each client, given a graph sample $\mathcal{G}$, DySFGC could obtain the encoded low- and high-pass signals:

$$\mathbf{H}_L = \Phi_K^L(\mathbf{L})\mathbf{X}, \quad \mathbf{H}_H = \Phi_K^H(\mathbf{L})\mathbf{X}. \tag{3}$$

where $\mathbf{H}_L, \mathbf{H}_H \in \mathbb{R}^{B \times F'}$ and F' is the latent dimension. DySFGC then uses the latent node representations to generate the global embeddings of the graph $\mathbf{h}_L, \mathbf{h}_H \in \mathbb{R}^{F'}$:

$$\mathbf{h}_L = \text{MeanPool}(\mathbf{H}_L), \quad \mathbf{h}_H = \text{MeanPool}(\mathbf{H}_H), \tag{4}$$

where $\text{MeanPool}(\cdot)$ is mean pooling operation. Next, DySFGC dynamically integrates high- and low-pass signals to generate band-pass signals and the corresponding global representations:

$$\begin{aligned} \mathbf{H}_B &= \text{MLP}_B(\alpha\mathbf{H}_L + (1-\alpha)\mathbf{H}_H), \\ \mathbf{h}_B &= \text{MeanPool}(\mathbf{H}_B). \end{aligned} \tag{5}$$

where $\alpha \in [0, 1]$ is a learnable parameter, $\mathbf{H}_B \in \mathbb{R}^{B \times F'}$ and $\mathbf{h}_B \in \mathbb{R}^{F'}$. Since the fixed parameters might be highly hypothetical and out of line with reality, a learnable α can not only cover signals in different frequency domains, but also fulfill the semantic information of the original features. Moreover, it is mainly optimized by reconstruction loss following the gradient flow of band-pass reconstruction, thereby preserving critical semantics in the original features. Finally, given the global representations of graphs, DySFGC can derive the global low-, high- and band-pass representations of graphs $\mathbf{Z}_L \in \mathbb{R}^{N \times F'} = [\mathbf{h}_L^1, \cdots, \mathbf{h}_L^N]$, $\mathbf{Z}_H \in \mathbb{R}^{N \times F'} = [\mathbf{h}_H^1, \cdots, \mathbf{h}_H^N]$ and $\mathbf{Z}_B \in \mathbb{R}^{N \times F'} = [\mathbf{h}_B^1, \cdots, \mathbf{h}_B^N]$ for each client.

In summary, the proposed learnable polynomial spectral filtering module ensures that the local filters in distributed clients capture more discriminative graph signals in different frequencies based on private datasets, fully extracting distinctive signals from every dataset.

4.2 Semantic-Aware Spectral Clustering

In each client, we hope to preserve the discriminative characteristics of signals in different frequencies while improving the semantics of global representations to improve the discriminative cluster-related expression. To enhance the distinct frequency semantics of signals, DySFGC first introduces the following spectral contrastive learning:

$$\begin{aligned} \mathcal{L}_L &= \mathbb{E}_{\mathcal{G}}[\log \mathcal{D}_L(\mathbf{Z}_L, \mathbf{Z}_B) + \log(1 - \mathcal{D}_L(\tilde{\mathbf{Z}}_L, \mathbf{Z}_B))], \\ \mathcal{L}_H &= \mathbb{E}_{\mathcal{G}}[\log \mathcal{D}_H(\mathbf{Z}_H, \mathbf{Z}_B) + \log(1 - \mathcal{D}_H(\tilde{\mathbf{Z}}_H, \mathbf{Z}_B))], \end{aligned} \tag{6}$$

where $\tilde{\mathbf{Z}}_H, \tilde{\mathbf{Z}}_L$ denote negative samples which is generated by random shuffling, and $\mathcal{D}_\phi(\mathbf{H}, \mathbf{h}) = \sigma(\mathbf{H}\mathbf{W}_\phi\mathbf{h}^\top), \phi \in \{L, H\}$ is a discriminator with learnable parameters $\mathbf{W} \in \mathbb{R}^{F' \times F'}$. Therefore, the spectral contrastive learning loss can be calculated as:

$$\mathcal{L}_{\text{con}} = (\mathcal{L}_L + \mathcal{L}_H) * 0.5. \tag{7}$$

We illustrate the theoretical intuition behind this loss. Although the fused band-pass representation is synthesized from these two components, using a non-linear mapping can create a distinct global view. By enforcing contrastive learning between the specific frequency views and the fused global view, we maximize the mutual information across different spectral channels because independent filters ensure the collaboration of frequency-specific signals instead of mutual conflict, thereby forcing the model to distill and retain the invariant structural semantics present in both the smooth topology and the localized structures, while discarding uninformative frequency-specific noise.

To obtain more expressive graph-level representations, DySFGC introduces a reconstruction with $\mathrm{MLP}_R(\cdot)$, which is widely applied in many fields [38, 39, 40, 41, 42, 43], to obtain global representations to preserve the critical semantics in the original graph and calculate the reconstruction loss:

$$\mathcal{L}_{\text{rec}} = \frac{1}{N}||\mathrm{MLP}_R(\mathbf{Z}_B) - \mathbf{Z}_o||_2. \tag{8}$$

The reconstruction of band-pass signals is critical for clustering. It utilizes the band-pass representations that integrate frequency-specific signals to model the original semantic information of the original graphs, which avoids distortion of latent embeddings used for clustering.

To evaluate the clustering properties and boost the cluster-related expression of graph samples, based on deep learning, DySFGC employs a soft clustering matrix $\mathbf{Q} \in \mathbb{R}^{N \times t}$ to evaluate the similarity between global representations of $\mathcal{G}_i$ and the j-th clustering centers $\mathbf{c}_j$ based on Student's t-distribution:

$$q_{ij} = \frac{(1 + ||\mathbf{z}_B^i - \mathbf{c}_j||^2)^{-1}}{\sum_{t=1}^{T}(1 + ||\mathbf{z}_B^i - \mathbf{c}_t||^2)^{-1}}, \tag{9}$$

where $\mathbf{c}_j$ is initialized by K-Means clustering algorithm. Then, DySFGC obtains the target distribution $\mathbf{P} \in \mathbb{R}^{N \times t}$:

$$p_{ij} = \frac{(q_{ij})^2 / \sum_i q_{ij}}{\sum_{t=1}^{T}(q_{it})^2 / \sum_i q_{it}}. \tag{10}$$

Finally, DySFGC utilizes the KL-divergence $\mathcal{D}_{\mathrm{KL}}(\cdot||\cdot)$ to measure the clustering loss between the soft distribution and the target distribution:

$$\mathcal{L}_{\text{kl}} = \mathcal{D}_{\mathrm{KL}}(\mathbf{P}||\mathbf{Q}) = \sum_i \sum_j p_{ij} \log \frac{p_{ij}}{q_{ij}}. \tag{11}$$

The merits of the semantic-aware spectral clustering module lie in: (1) It effectively discriminates different semantic information about spectral signals using contrastive learning and reconstruction to precisely collect graph-specific characteristics; (2) It captures the category characteristics of graph samples to enhance the clustering via a KL divergence.

4.3 Dynamic Spectral Consensus

Different from traditional federated consensus generation [44, 16, 30], we introduce a dynamic spectral consensus generation strategy, which has two primary novel distinctions from existing methods. First, we introduce a multi-channel updating mechanism that separately updates the parameters of different frequencies. The motivation is that different frequency domains contain distinct semantic information about graphs, resulting in the discrepancy in potential knowledge learned by DySFGC. For example, high-pass singals is only captured by high-pass filters. This phenomenon encourages us to consider isolating the parameter update process through frequency-specific channels to obtain spectral consensus with more accurate semantics. Second, we introduce a client updating process integrated with the traditional server updating process. The intuition is that the existing updating mechanism directly downloads the consensus as the learnable parameters of distributed clients, which completely loses the private characteristics of local samples. However, we believe that the comprehensive global knowledge can improve the generalization of local models, but it cannot completely replace the local characteristics of distributed clients. Adaptive fusion of global and local knowledge can refine local generalization and alleviate cross-client heterogeneity.

Multi-Channel Updating Mechanism To capture more discriminative consensus in the spectral domain, DySFGC first implements a multi-channel updating mechanism. Specifically, the low-pass filter Φ_K^L and the low-pass discriminator $\mathcal{D}_L$ are exclusive for low-frequency encoding; their parameters are designed to follow the low-pass updating channel. Similarly, the parameters in the high-pass filter Φ_K^H and the high-pass discriminator $\mathcal{D}_H$ follow the high-pass updating channel. MLP_B and MLP_R follow a band-pass updating channel since their input is band-pass signals. Formally, for client C_m, we denote the learnable parameters in low-, high- and band-pass channel updating channel at t-th iteration ($t \geq 0$), respectively, as $\theta_L^m(t)$, $\theta_H^m(t)$, and $\theta_B^m(t)$. The corresponding global parameters in the server is $\theta_L^g(t)$, $\theta_H^g(t)$ and $\theta_B^g(t)$.

Dynamic Updating Mechanism We design a novel dynamic updating mechanism for different channels, including the server updating process and the client updating process, to address the second limitation.

(1) Server Updating Process. Take the low-pass channel as an example. To better balance the contribution of the local client to the server, we consider the difference of the parameters between client and server, which is denoted as $\Delta_s\theta_L^m(t) = \theta_L^m(t) - \theta_L^g(t)$. Meanwhile, to better evaluate the model learning ability, we consider preserving the original parameters in the server dynamically. The updating process can be defined as:

$$\theta_L^g(t+1) = (1-\kappa_L)\theta_L^g(t) + \kappa_L \sum_{C_m \in \mathcal{C}} \eta_L^m \Delta_s \theta_L^m(t). \tag{12}$$

Wherein, $\eta_L^m = \Phi(|\frac{\Delta_s\theta_L^m}{\sum_{C_i\in\mathcal{C}}\Delta_s\theta_L^i}|)$ is the aggregation coefficient, which aims to balance the contributions of different clients. $\Phi(\cdot)$ is mean function along all dimension. $\kappa_L = \frac{1}{1+\exp(-\Delta_L^o)}$ is a gated coefficient, where $\Delta_L^o = \Phi(\sum_{C_m\in\mathcal{C}}\Delta_s\theta_L^m(t) - \theta_L^g(t))$. It dynamically evaluates the contribution of the server's original global consensus in the updating process. Similarly, we can obtain the updating process for high- and band-pass channels:

$$\theta_H^g(t+1) = (1-\kappa_H)\theta_H^g(t) + \kappa_H \sum_{C_m \in \mathcal{C}} \eta_H^m \Delta_s \theta_H^m, \tag{13}$$

$$\theta_B^g(t+1) = (1-\kappa_B)\theta_B^g(t) + \kappa_B \sum_{C_m \in \mathcal{C}} \eta_B^m \Delta_s \theta_B^m, \tag{14}$$

where $\eta_H^m = \Phi(|\frac{\Delta_s\theta_H^m}{\sum_{C_i\in\mathcal{C}}\Delta_s\theta_H^i}|)$, $\eta_B^m = \Phi(|\frac{\Delta_s\theta_B^m}{\sum_{C_i\in\mathcal{C}}\Delta_s\theta_B^i}|)$ are aggregation coefficients respectively for high- and band-pass channels, $\kappa_H = \frac{1}{1+\exp(-\Delta_H^o)}$, $\kappa_B = \frac{1}{1+\exp(-\Delta_B^o)}$ are the gated coefficients

respectively for high- and band-pass channels, and $\Delta_H^o = \Phi(\frac{1}{M}\sum_{C_m\in\mathcal{C}}\Delta_s\theta_H^m - \theta_H^g(t))$ and $\Delta_B^o = \Phi(\frac{1}{M}\sum_{C_m\in\mathcal{C}}\Delta_s\theta_B^m - \theta_B^g(t))$.

(2) Client Updating Process. To better preserve the semantics of local clients, we set a gate coefficient for the local client when downloading the global parameters for the server. Take the low-pass channel as an example. Specifically, we denote the updated global parameters at t-th iteration as $\theta_L^g(t)$, and the parameters of local client C_m at $(t+1)$-th iteration as $\theta_L^m(t+1)$. We denote the difference between the updated global parameters and the local as $\Delta_c\theta_L^m = \theta_L^g(t+1) - \theta_L^m(t)$. The client updating process can be formulated as:

$$\theta_L^m(t+1) = (1-\epsilon_L^m)\theta_L^g(t+1) + \epsilon_L^m\theta_L^m(t), \tag{15}$$

where $\epsilon_L^m = \Phi(\frac{\Delta_c\theta_L^m}{\sum_{C_i\in\mathcal{C}}\Delta_c\theta_L^i})$ is the gate coefficient for clients. If the difference between the server and client C_m is relatively small, ϵ_L^m has a relatively small value, indicating that the updating process of client C_m focuses more on global consensus. However, if the global consensus shows less consistency with the local client, the update process will focus more on the client itself. In this way, it can maintain private properties while obtaining global consensus, effectively avoiding performance degradation caused by distribution shifts in the frequency domains. Similar to the low-pass channel, we can obtain the client updating process for high- and band-pass channels:

$$\theta_H^m(t+1) = (1-\epsilon_H^m)\theta_H^g(t) + \epsilon_H^m\theta_H^m(t), \tag{16}$$

$$\theta_B^m(t+1) = (1-\epsilon_B^m)\theta_B^g(t) + \epsilon_B^m\theta_B^m(t), \tag{17}$$

where $\epsilon_H^m = \Phi(\frac{\Delta_c\theta_H^m}{\sum_{C_i\in\mathcal{C}}\Delta_c\theta_H^i})$ and $\epsilon_B^m = \Phi(\frac{\Delta_c\theta_B^m}{\sum_{C_i\in\mathcal{C}}\Delta_c\theta_B^i})$.

The proposed dynamic spectral consensus module offers two benefits: (1) It introduces a frequency-specific updating mechanism to refine the learning process of model parameters according to different frequency characteristics; (2) The update of the server and clients can dynamically balance the mutual contributions and ensure the adaptive preservation of original semantics, which guarantees the effective synergy between private characteristics and global consensus.

4.4 Optimization Objective and Training

The overall loss function is as follows:

$$\mathcal{L} = \mathcal{L}_{\text{kl}} + \zeta_1\mathcal{L}_{\text{con}} + \zeta_2\mathcal{L}_{\text{rec}}, \tag{18}$$

where ζ_1, ζ_2 are hyperparameters.

5 Experiments

5.1 Experimental setup

Datasets and Baselines To verify the effectiveness of DySFGC, following [16], we employ 15 graph datasets across different domains [45], including: (1) SM (MU-TAG, BZR, COX2, DHFR, PTC_MP, AIDS, BZR_MD), SY (SYNTHETIC), SN (COLLAB, IMDB-MULTI), BIO (DD, PROTEINS), and CV (Letter-high, Letter-low, Letter-med). In the FGC problem, five types of non-IID settings are generated: (1) 2 clusters within the same domain (SM); (2) 3 clusters within the same domain (SN); (3) 15 clusters within the same domain (CV); (4) 2 clusters across two domains (SM-BIO); (5) 2 clusters across three domains (SM-BIO-SY). We select eleven state-of-the-art baselines, including three types: (1) Traditional graph clustering methods, DBGCN [8] and S2CAG [46]; (2) FGL methods, FedTAD [47], FedIIH [33], FedSPA [48], S2FGL [34], GuardFGL [49], FedGM [31], FedC4 [50], and FedHERO [51]; (3) A FGC method, FedGCN [16].

Implementation and Metrics The Adam optimizer is utilized, and the learning rate is 1e-3. The hidden size F' is set to 128. The training and communication epochs, T_c and T_s, are respectively set to 100 and 30. Hyperparameters ζ_1, ζ_2 are respectively set to 1 and 0.8. The filter order is set to 4. We evaluate DySFGC with four classical clustering metrics compared with all baselines [52, 53, 54]: Accuracy (ACC), Normalized Mutual Information (NMI), Adjusted Rand Index (ARI), and F1 Score (F1).

Table 1: The performance on five datasets under unsupervised settings. The results are in %.

Domain	Metric	DBGCN	S2CAG	FedTAD	FedIIH	FedSPA	S2FGL	GuardFGL	FedGM	FedC4	FedHERO	FedGCN	DySFGC
SM	ACC	58.9±2.2	61.4±3.1	45.3±2.6	57.6±1.8	62.1±2.4	52.1±2.0	68.5±1.5	58.3±2.3	49.1±2.7	60.8±1.9	75.9±2.1	**78.9**±0.9
	NMI	12.0±1.4	11.6±2.8	9.02±2.1	11.8±1.6	12.8±2.3	10.5±1.9	19.2±1.3	12.6±2.5	9.5±2.2	17.1±1.5	24.9±2.0	**27.9**±0.8
	ARI	0.1±1.9	4.9±2.4	2.5±1.6	5.2±2.1	13.8±2.5	8.9±1.7	30.3±2.2	15.9±1.8	2.7±2.3	26.2±1.4	31.1±3.2	**34.1**±0.7
	F1	49.7±2.5	55.2±1.8	38.9±3.1	48.8±2.2	57.1±1.6	44.5±2.4	61.2±1.4	47.5±2.7	39.5±2.0	57.9±1.9	67.1±2.3	**70.1**±1.1
SM-BIO	ACC	59.5±2.1	65.2±3.8	50.6±2.5	55.2±1.9	62.6±2.3	56.8±2.0	70.8±1.7	61.2±2.4	53.5±2.2	70.9±1.8	69.2±1.5	**73.9**±0.8
	NMI	5.3±1.9	6.8±2.5	4.9±2.1	5.1±1.6	7.8±2.4	6.6±1.8	13.5±2.2	10.5±1.5	6.4±1.7	10.5±2.0	14.0±2.9	**17.0**±0.7
	ARI	3.8±2.6	7.2±2.1	2.6±1.8	3.7±2.3	9.2±1.9	3.4±1.5	13.8±2.4	10.9±1.7	5.6±2.0	11.8±1.4	17.5±3.2	**20.5**±0.6
	F1	51.7±1.8	55.9±2.7	46.9±2.2	51.7±1.5	48.6±2.1	57.3±2.5	60.3±1.9	50.3±1.6	40.4±2.4	52.4±1.3	59.1±1.7	**63.3**±0.8
SM-BIO-SY	ACC	57.9±2.8	54.2±1.9	61.6±2.3	66.5±1.7	69.0±2.1	57.8±2.5	60.2±1.8	67.1±2.0	62.5±1.6	70.2±2.2	68.6±1.9	**73.2**±0.9
	NMI	15.7±2.6	13.9±3.1	16.5±2.4	16.8±1.9	19.9±2.2	12.6±2.0	15.4±1.7	16.3±2.3	17.1±1.5	25.3±1.8	13.5±2.5	**28.3**±0.8
	ARI	16.1±3.2	14.9±2.7	13.6±2.1	15.0±1.8	16.3±2.5	13.2±1.6	17.6±2.3	14.4±1.9	11.3±2.0	17.9±1.5	17.2±3.6	**20.9**±0.7
	F1	52.3±2.4	51.0±3.5	54.2±2.0	50.8±2.6	60.0±1.9	50.8±2.3	54.6±1.7	58.9±2.1	54.2±1.8	60.5±2.2	59.4±3.8	**63.5**±1.0
SN	ACC	51.7±3.1	55.5±2.4	53.9±2.7	55.8±1.9	58.1±2.3	58.9±2.0	62.8±2.6	60.5±1.8	56.2±2.2	61.5±2.1	66.6±2.3	**69.6**±1.1
	NMI	13.7±3.5	15.5±2.9	15.7±2.6	17.9±2.2	18.6±2.4	18.9±2.1	25.6±2.7	21.6±1.9	16.6±1.8	22.1±2.3	30.4±6.6	**33.4**±0.9
	ARI	12.4±2.2	14.9±3.2	13.4±2.0	16.5±2.4	18.0±1.8	21.1±2.3	28.5±1.6	21.1±2.1	20.8±1.7	24.7±1.9	34.1±5.3	**37.1**±1.0
	F1	50.7±2.5	54.3±1.8	52.6±2.1	46.5±2.3	51.3±2.6	53.7±2.0	58.8±1.7	56.7±1.4	46.3±1.9	52.7±1.6	50.7±2.4	**61.8**±0.8
CV	ACC	12.4±3.1	15.9±2.4	11.2±2.8	13.1±1.9	15.0±2.5	20.6±2.2	16.3±2.6	22.4±2.0	21.9±2.3	24.8±1.8	34.6±3.2	**37.6**±0.9
	NMI	20.4±2.7	18.5±2.3	18.6±2.5	20.4±1.9	20.6±2.4	22.1±1.6	15.6±3.4	20.6±2.1	21.3±2.2	23.5±1.7	34.2±1.5	**37.2**±0.8
	ARI	15.3±2.3	16.7±3.0	10.9±2.1	11.4±1.8	13.1±2.2	12.1±1.5	13.9±2.0	11.6±1.7	13.5±1.9	13.7±1.4	19.3±2.1	**22.3**±0.7
	F1	11.6±1.8	14.7±3.3	10.7±2.4	12.1±1.6	13.9±2.1	15.8±1.9	13.7±1.5	17.9±2.2	16.8±1.7	20.2±1.4	31.6±2.9	**34.6**±0.8

5.2 Experimental Results and Analysis

Performance in Unsupervised Settings To evaluate the advancement of DySFGC, we implement unsupervised clustering experiments. Since most baselines are designed for supervised learning, we extend them to an unsupervised paradigm to keep fairness. The results are shown in Table 1, where the best observations are highlighted in bold, and the runner-up is underlined. From the observations, DySFGC outperforms baselines consistently on five domains. The reason can be attributed to: (1) DySFGC captures the graph signals with different frequencies and introduces spectral contrastive learning and reconstruction loss, which extract more spectral semantic information compared with baselines that focus on the spatial domain; (2) DySFGC implements multi-channel and dynamic parameter interactions between distributed clients and the server, which help local models capture frequency-specific spectral consensus while dynamically integrating parameters based on the contributions to generate comprehensive global consensus.

Table 2: The performance on five datasets under supervised settings with respect to ACC and NMI. The results are in %.

Domain	Metric	DBGCN	S2CAG	FedTAD	FedIIH	FedSPA	S2FGL	GuardFGL	FedGM	FedC4	FedHERO	FedGCN	DySFGC
SM	ACC	61.8±2.1	64.2±3.6	48.9±2.8	60.9±1.9	64.8±2.5	55.1±2.3	71.2±1.7	61.0±2.2	52.4±3.1	63.5±1.8	78.2±2.7	**81.2**±1.0
	NMI	14.8±1.5	15.2±3.2	12.4±2.1	14.9±1.7	15.8±2.3	13.2±1.9	22.3±1.4	15.7±2.6	12.6±2.0	20.2±1.6	27.4±2.2	**30.4**±0.9
SM-BIO	ACC	62.1±2.3	67.8±4.2	54.2±2.1	58.6±1.9	65.1±2.4	59.4±2.7	73.1±1.5	64.0±1.8	56.8±2.5	73.5±2.0	71.4±1.3	**76.5**±1.1
	NMI	6.6±1.9	8.1±2.4	8.1±2.1	8.7±1.8	11.2±1.6	9.8±2.2	16.4±1.4	13.7±1.7	9.5±1.5	13.4±2.0	16.3±2.9	**19.4**±0.7
SM-BIO-SY	ACC	60.8±2.9	57.4±2.2	64.1±2.5	68.8±1.8	71.0±2.1	60.3±2.4	63.0±2.7	69.2±1.6	65.0±2.0	72.4±1.9	70.5±1.5	**75.4**±0.8
	NMI	18.9±2.6	17.1±3.1	19.4±2.3	19.6±1.7	22.0±2.0	15.4±2.5	18.1±2.2	18.9±1.5	19.6±1.9	27.4±1.4	15.7±2.8	**30.4**±0.6
SN	ACC	54.6±3.1	58.2±2.4	56.7±2.8	58.5±1.9	60.6±2.2	61.2±1.7	65.1±2.5	63.0±2.0	58.8±2.3	64.0±1.8	68.7±2.9	**71.7**±0.9
	NMI	16.9±3.4	18.6±2.7	18.3±3.0	20.3±2.2	20.8±2.5	21.1±2.1	28.0±2.4	24.0±1.9	19.3±1.7	24.4±2.0	32.7±6.6	**35.7**±1.1
CV	ACC	15.2±2.9	18.4±2.5	14.0±3.2	15.6±1.8	17.8±2.4	22.9±2.1	19.1±2.7	24.9±2.2	24.2±2.0	27.1±1.9	36.8±3.1	**39.8**±1.0
	NMI	23.0±3.1	21.0±2.8	21.2±2.5	22.6±2.1	22.8±2.6	24.2±1.9	18.1±3.4	22.9±2.0	23.5±2.3	25.6±2.2	36.1±1.6	**39.1**±0.8

Performance in Supervised Settings To better verify the superiority of DySFGC, we implement supervised federated learning for traditional FGL baselines. Specifically, following [16], for the CV domain datasets, one true label is assigned to each class, while for the other domain datasets, five true labels are assigned to each class. As shown in Table 2, DySFGC still achieves superior observations over traditional FGL baselines with supervised information across diverse domains, further demonstrating the advancement

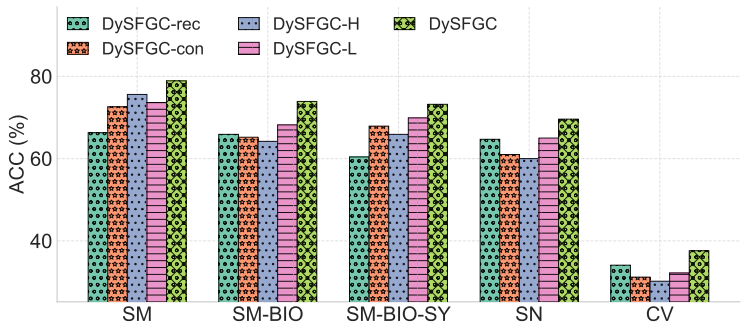


Figure 2: The performance of loss function rationality experiments.

of DySFGC. We can also discover that with supervised signals, the models generally achieve better performance compared with unsupervised settings.

Loss Function Rationality To evaluate the contributions of the loss components, we compare DySFGC with four variants: DySFGC-rec, DySFGC-con, DySFGC-H, and DySFGC-L remove reconstruction, contrastive learning, $\mathcal{L}_H$, and $\mathcal{L}_L$, respectively. In Fig. 2, the full model achieves the highest ACC on all five domains. Removing reconstruction or contrastive learning reduces ACC, although the relative effect depends on the domain: removing reconstruction yields a larger reduction on SM and SM-BIO-SY, whereas removing contrastive learning yields a larger reduction on SM-BIO, SN, and CV. The high-pass and low-pass ablations also reduce ACC across all five domains.

Sensitivity We explore the sensitivity of hyperparameters, including loss function hyperparameters ζ_1, ζ_2. Fig. 3 exhibit the sensitivity experiments of ζ_1 and ζ_2. The observations show slight performance degradation when the values of hyperparameters are relatively small. This is because small values compromise the contribution of corresponding modules. As the values increase, the performance tends to plateau.

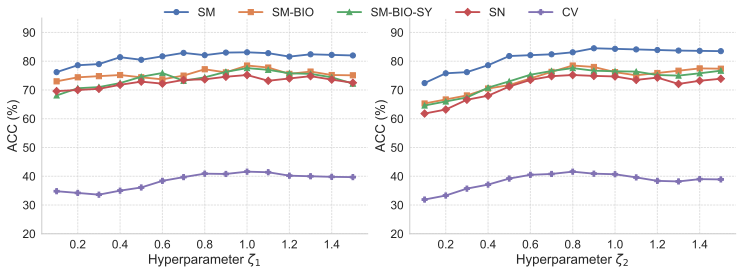


Figure 3: The sensitivity experiments for ζ_1 and ζ_2.

Dynamic Spectral Consensus Rationality We compare three variants to evaluate the dynamic spectral consensus module: DySFGC-MCUM removes multi-channel updating, DySFGC-SUP removes server updating, and DySFGC-CUP removes client updating. In Fig. 4, DySFGC achieves the highest ACC on four of the five domains and the highest F1 on three domains. DySFGC-SUP is slightly higher on SN ACC (69.8 versus 69.6), SM F1 (70.2 versus 70.1), and CV F1 (34.9 versus 34.6). The reported results therefore show benefits on most domain–metric combinations rather than uniform improvements.

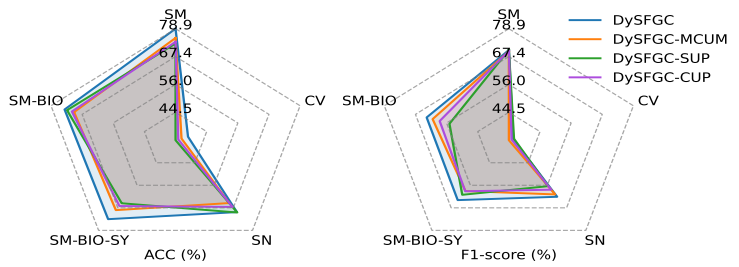


Figure 4: The dynamic spectral consensus rationality experiments.

6 Conclusion

In this paper, we explore spectral federated graph-level clustering, which is the first attempt to exploit the influences of graph signals at different frequencies on the clustering. To address this problem, we develop a novel dynamic spectral federated graph-level clustering (DySFGC). DySFGC extracts discriminative cluster-related semantic information about spectral signals using learnable graph filters. DySFGC also deploys different channels to update spectral consensus with dynamic weights, which helps the private clients enhance the clustering. Extensive experiments on five groups of datasets demonstrate the superiority of DySFGC over eleven baselines. In the future, we plan to extend the generalization capacity of DySFGC to more complex and challenging issues in FGC, such as fairness [55] and heterophily [56].

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