Spectral clustering and model reduction for weakly-connected coherent network systems

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Abstract—We propose a novel model-reduction methodology for large-scale dynamic networks with tightly-connected components. First, the coherent groups are identified by a spectral clustering algorithm on the graph Laplacian matrix that models the network feedback. Then, a reduced network is built, where each node represents the aggregate dynamics of each coherent group, and the reduced network captures the dynamic coupling between the groups. Our approach is theoretically justified under a random graph setting. Finally, numerical experiments align with and validate our theoretical findings.

I. INTRODUCTION

In networked dynamical systems, coherence refers to a coordinated behavior from a group of nodes such that all nodes have similar dynamical responses to some external disturbances. Coherence analysis is useful in understanding the collective behavior of large networks including consensus networks [1], transportation networks [2], and power networks [3]. However, little we know about the underlying mechanism that causes such a coherent behavior in various networks.

Classic slow coherence analyses [3]–[7] (with applications mostly to power networks) usually consider the second-order electro-mechanical model without damping: \( \dot{x} = -M^{-1}Lx \), where \( M \) is the diagonal matrix of machine inertias, and \( L \) is the Laplacian matrix whose elements are synchronizing coefficients between pair of machines. The coherency or synchrony [4] (a generalized notion of coherency) is identified by studying the first few slowest eigenmodes (eigenvectors with small eigenvalues) of \( M^{-1}L \), the analysis can be carried over to the case of uniform [3] and non-uniform [5] damping. However, such state-space-based analysis is limited to very specific node dynamics (second order) and do not account for, more complex dynamics or controllers that are usually present at a node level; e.g., in the power systems literature [8]–[10]. Therefore, we need a coherence identification procedure that works for more general node dynamics.

Recently, it has been theoretically established that coherence naturally emerges when a group of nodes are tightly-connected, regardless of the node dynamics, as long as the interconnection remains stable [11], [12]. The analysis also provides an asymptotically (as the network connectivity increases) exact characterization of the coherent response, which amounts an harmonic sum of individual node transfer functions. Thus, in a sense, coherence identification is closely related to the problem of finding tightly connected components in the network, for which many clustering algorithms based on the spectral embedding of graph adjacency or Laplacian matrix, are proposed and theoretically justified [13].

This leads to the natural question: Can these graph-based clustering algorithms be adopted for coherence identification in networked dynamical systems? Intuitively, when we apply those clustering algorithms to identify tightly-connected components in the network, each component should be coherent also in the dynamical sense. Then, applying [11], [12] for each cluster, should lead to a good model for each coherent group, which after interconnected with an appropriately chosen reduced graph should lead to a good network-reduced aggregate model of the dynamic interactions among across coherent components.

In this paper, we formalize and theoretically justify this seemingly naïve approach utilizing the recent frequency-domain analysis for coherence [12] and dynamics aggregation [14]. Specifically, we propose a novel approximation model for large-scale networks with two tightly-connected components/groups. The model is constructed in two stages: First, the coherent groups are identified by a spectral clustering algorithm solely on the graph Laplacian matrix of the network; then a two-node network, in which each node represents the aggregate dynamics of one coherent group, approximates the dynamical interactions between the two coherent groups in the original network. We show that our algorithm achieves perfect clustering for coherence identification and has good accuracy in modeling the inter-group dynamical interaction in the network with high probability when the network graph is randomly generated from a weight stochastic block model. Lastly, we apply our algorithm to modeling the frequency response in power networks with IEEE 68-bus test system, and the numerical results align with our theoretical findings.

Unlike previous coherence analysis [3]–[5], our approach is dynamic-agnostic in that the coherence is identified solely by network connections, which works for the case when nodes are equipped with complicated controllers. Moreover, our model is suitable for the control design aiming mostly at response shaping [9] as the proposed two-node model clearly shows how implemented controller would affect the aggregate dynamics and the inter-group interaction.

The rest of the paper is organized as follows: We formalize the coherence identification problem in Section II and also introduce the spectral clustering algorithm. Then we propose
our approximation model in Section III and provide theoretical justification in Section IV. Lastly, we validate our model by several numerical experiments in Section V.

Notation: For a vector $x$, $\|x\| = \sqrt{x^T x}$ denotes the 2-norm of $x$, $[x]_i$ denotes its $i$-th entry, and for a matrix $A$, $\|A\|$ denotes the spectral norm. We let $I_n$ denote the identity matrix of order $n$. $V^T$ denote the conjugate transpose of matrix $V$, $\Pi_n$ denote $[1, \ldots, 1]^T$ with dimension $n$, and $[n]$ denote the set $\{1, 2, \ldots, n\}$. For non-negative random variables $X(n), Y(n)$, ordering, we write $X(n) \sim O_p(Y(n))$ if $\exists M > 0$, s.t. $\lim_{n \to \infty} P(X(n) \leq MY(n)) = 1$. We write $f(n) \sim O_p(g(n))$ if $\exists M > 0$, s.t. $\lim_{n \to \infty} P(X(n) \geq MY(n)) = 1$.

II. PRELIMINARIES

A. Network Model

Consider a network consisting of $n$ nodes ($n \geq 2$), indexed by $i \in [n]$ with the block diagram structure in Fig I. $L$ is the Laplacian matrix of an undirected, weighted graph that describes the network interconnection. We further use $f(s)$ to denote the transfer function representing the dynamics of the network coupling, and $G(s) = \text{diag}(g_i(s))$ to denote the nodal dynamics, with $g_i(s), i \in [n]$, being an SISO transfer function representing the dynamics of node $i$. The network takes a vector input $u = [u_1, \ldots, u_n]^T$ as

\begin{align*}
\text{Fig. 1: Block Diagram of General Networked Dynamical Systems}
\end{align*}

input, whose component $u_i$ is the disturbance or input to node $i$. The network output $y = [y_1, \ldots, y_n]^T$ contains the individual node outputs $y_i, i = 1, \ldots, n$. We are interested in characterizing and approximating the response of the transfer matrix $T_{yu}(s)$ under certain assumptions on the network topology, i.e., the Laplacian matrix $L$.

Many existing networks can be represented by this structure. For example, for the first-order consensus network [1], $f(s) = 1$, and the node dynamics are given by $g_i(s) = \frac{1}{s}$. For power networks [15], $f(s) = \frac{1}{s}$, $g_i(s)$ are the dynamics of the generators, and $L$ is the Laplacian matrix representing the sensitivity of power injection w.r.t. bus phase angles. Finally, in transportation networks [16], $g_i(s)$ represent the vehicle dynamics whereas $f(s)L$ describes local inter-vehicle information transfer.

Recent work [11], [12] has shown that, under mild assumptions, the following holds[1]

\begin{align*}
\lim_{\lambda_2(L) \to \infty} \|T_{yu}(s_0) - \hat{g}(s_0)\Pi^T\| = 0,
\end{align*}

where

\begin{align*}
\hat{g}(s) = \left( \sum_{i=1}^{n} g_i^{-1}(s) \right)^{-1}.
\end{align*}

That is, when the algebraic connectivity $\lambda_2(L)$ of the network is high, one can approximate $T_{yu}(s)$ by a rank-one transfer matrix. Such a rank-one transfer matrix $\hat{g}(s_0)\Pi^T$ precisely describes the coherent behavior of the network: The network takes the aggregated input $\hat{u} = \Pi^T u = \sum_{i=1}^{n} u_i$, and responds coherently as $\hat{y}\Pi$, where $\hat{y} = \hat{g}(s)\hat{u}$. Therefore, it suffices to study $\hat{g}(s)$ to understand the coherent behavior in a tightly-connected network.

However, practical networks are not necessarily tightly-connected. Instead, they often contain multiple groups of nodes such that within each group, the nodes are tightly-connected while between groups, the nodes are weakly-connected. Then the network dynamics can be reduced to dynamic interactions among these groups. In order to approximate such interaction, it is natural to, first identify coherent groups, or coherent areas, in the network, then apply the aforementioned analysis to obtain the coherent dynamics $\hat{g}(s)$ for each group, and replace the entire coherent group by an aggregate node with $\hat{g}(s)$. But the question remains as to how one would identify coherent groups to start with, and how should we model the interaction among aggregate nodes such that it approximates the interaction among coherent groups in the original network. We start with the problem of identifying coherent groups.

B. Spectral Clustering

Spectral clustering [17] is a popular technique for identifying tightly-connected components in a network. Algorithm I describes its simplest form for identifying two groups in a network based on the graph Laplacian matrix $L$. The algorithm computes the eigenvector $v_2(L)$ of $L$ associated with the second smallest eigenvalue $\lambda_2(L)$, and group the nodes based on the sign of entries of $[v_2(L)]_i, i = 1, \ldots, n$, so that nodes with non-negative $[v_2(L)]_i$, are in one group, and others in another group.

Algorithm 1: Spectral Clustering for detecting two communities

Data: Symmetric Laplacian Matrix $L$
Find $\lambda_2(L), v_2(L)$ from the eigendecomposition of $L$
$I_a \leftarrow \emptyset, I_b \leftarrow \emptyset$

for $i = 1, \ldots, n$ do

if $[v_2(L)]_i \geq 0$ then

$I_a \leftarrow I_a \cup \{i\}$

else

$I_b \leftarrow I_b \cup \{i\}$

Result: $I_a, I_b, \lambda_2(L)$

If the network connection has a block structure, then such a simple algorithm performs well. More precisely, suppose the Laplacian matrix is of the following form:

\begin{align*}
L_{blk} = D - A_{blk}.
\end{align*}
where, $n_a + n_b = n$, and $0 \leq \beta \leq \alpha$. Then such a network has, by construction, two coherent groups: one consisting of the first $n_a$ nodes and another consisting of the remaining $n_b$ nodes. From the adjacency matrix $A_{\text{blk}}$, it is clear that the nodes in the same coherent group are tightly connected while the nodes from different group are relatively weakly connected (since $\beta \leq \alpha$). One can show that

$$v_2(L_{\text{blk}}) = \frac{1}{\sqrt{n}} \begin{bmatrix} \frac{\sqrt{n}}{n_a} \mathbb{1}_{n_a} \mathbb{1}^T_{n_a} \\ -\frac{\sqrt{n}}{n_b} \mathbb{1}_{n_b} \end{bmatrix},$$

from which Algorithm 1 groups first $n_a$ nodes into one group and the rest $n_b$ into the other group.

Obviously, one would not expect such a densely connected network in practice, then how does spectral clustering remain effective? Previous work studied the spectral clustering algorithm (and its variants) on random graphs generated from the Stochastic Block Model [18], where, in its simplest form with two communities/groups, the edge between every two nodes appears in the network independently with some probability, such that intra-group edges appear more often than inter-group edges. This randomly generated adjacency matrix $A$ has expected value of the form $L = \sum_{i=1}^n \lambda_i(L)v_i(L)v_i^T(L)$, and under an approximation by a rank-one transfer matrix, we first define

$$T_2(s) = \left[ \frac{1}{\sqrt{n}} v_2(L) \right] H_2^{-1} \left[ \frac{1}{\sqrt{n}} v_2^T(L) \right],$$

where

$$H_2(s) = \left[ \frac{1}{\sqrt{n}} G^{-1}(s) \right] \left[ \frac{1}{\sqrt{n}} v_2^T(L) G^{-1}(s) \right] v_2(L) + \lambda_2(L)f(s).$$

Then our main result is the following:

**Theorem 1.** For $s_0 \in \mathbb{C}$ that is not a pole of $f(s)$ and has these two quantities

$$\|T_2(s_0)\| := M_1, \quad \max_{1 \leq i \leq n} |g_i^{-1}(s_0)| := M_2,$$

finite. Then whenever $|f(s_0)|\lambda_3(L) \geq M_2 + M_1 M_2^2$, the following inequality holds:

$$\|T_{yu}(s_0) - T_2(s_0)\| \leq \frac{(M_1 M_2 + 1)^2}{|f(s_0)| \lambda_3(L) - M_2 - M_1 M_2^2}.$$

The proof is shown in Appendix. The theorem states that for almost any $s_0 \in \mathbb{C}$, except for poles of $T_2(s)$, zeros of $g_i(s)$ and pole of $f(s)$, one can approximate $T_{yu}(s)$ by a rank-two transfer matrix $T_2(s)$, in frequency domain. While establishing the relations between $T_{yu}(s)$ and $T_2(s)$ regarding the time-domain response is left as future research, this theorem suggests that when the network has large $\lambda_3(L)$, the network dynamics can be potentially understood by studying $T_2(s)$.

**B. Preliminary Case: Dense Graph with Two-blocks Structure**

While studying $T_2(s)$ itself can be interesting, we will show that under certain assumptions on the network topology, $T_2(s)$ has an even simpler and more interpretable form.

Let us thus assume the network has the Laplacian matrix as in [3]:

$$L_{\text{blk}} = D - A_{\text{blk}},$$

where, $n_a + n_b = n$, and $0 \leq \beta \leq \alpha$. Without loss of generality, we assume $n_a \geq n_b$. We start with the following statement regarding the eigenvalues and eigenvectors of $L_{\text{blk}}$:

**Claim.** For the Laplacian matrix $L_{\text{blk}}$ defined in [3] with $\alpha, \beta \geq 0$ and $n_a \geq n_b$, we have

1) $\lambda_2(L_{\text{blk}}) = n\beta, v_2(L_{\text{blk}}) = \frac{1}{\sqrt{n}} \begin{bmatrix} \sqrt{n} \mathbb{1}_{n_a} \mathbb{1}^T_{n_a} \\ -\sqrt{n} \mathbb{1}_{n_b} \mathbb{1}^T_{n_b} \end{bmatrix};$

2) $\lambda_3(L_{\text{blk}}) = n_b\alpha + n_a\beta.$
We have shown that $T_2(s)$ approximate $T_{yu}(s)$ well if $\lambda_3(L)$ is large. Given weak inter-area connectivity, namely a small $\beta$, $\lambda_3(L_{\text{blk}})$ is large when 1) $\alpha$, the in-area connection, is large; and 2) $n_b$ is not too small, i.e., the two coherent groups has balanced size. The two conditions are reasonable: we require the former for the coherence to emerge in the first place, and the later excludes the case where the network are dominated by one large coherent group.

More importantly, the eigenvector $v_2(L_{\text{blk}})$, which is used to define $T_2(s)$, has an simple expression. In this case, the symmetric $H_2(s)$ in (4) can be written as

$$H_2(s) = \left[ \frac{1}{n} (\tilde{g}_a^{-1}(s) + \tilde{g}_b^{-1}(s)) + \lambda_2(L) f(s) \right],$$

where

$$\tilde{g}_a(s) = \left( \sum_{i} g_i^{-1}(s) \right)^{-1}, \quad \tilde{g}_b(s) = \left( \sum_{i=n_a+1}^{n} g_i^{-1}(s) \right)^{-1},$$

are exactly the aggregate dynamics for each coherent group as defined in (2). Such expression for $H_2(s)$ suggests that one may be able to represent $T_2(s)$ by some interconnection among $\tilde{g}_a(s), \tilde{g}_b(s)$ and $f(s)$, and this is indeed true:

**Theorem 2.** Consider a network of two nodes interconnected as in Fig. 7 with node dynamics $G(s) := \hat{G}(s) = \begin{bmatrix} \tilde{g}_a(s) & 0 \\ 0 & \tilde{g}_b(s) \end{bmatrix}$ and Laplacian matrix $L := \tilde{L} = \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$, and let $\hat{T}_2(s)$ be the $2 \times 2$ transfer matrix from the network input $\hat{u} = \begin{bmatrix} \tilde{u}_a \\ \tilde{u}_b \end{bmatrix}$ to the output $\hat{y} = \begin{bmatrix} \tilde{y}_a \\ \tilde{y}_b \end{bmatrix}$. Then for networks with Laplacian matrix $L_{\text{blk}}$ defined in (3), we have

$$T_2(s) = \begin{bmatrix} I_{n_a} & 0 \\ 0 & I_{n_b} \end{bmatrix} \hat{T}_2(s) \begin{bmatrix} I_{n_a} \\ 0 \end{bmatrix} = \begin{bmatrix} \tilde{u}_a \\ \tilde{u}_b \end{bmatrix}$$

that spectral clustering performs well on certain random graphs as long as the expected Adjacency matrix has the desired block structure [18]. We argue that the same holds for our algorithm.

Now consider a random weighted graph of size $n$ whose adjacency matrix $A = [A_{ij}]$ is generated as

$$A_{ij} = \begin{cases} W_{ij}, & \text{with probability } P_{ij} \\ 0, & \text{with probability } 1 - P_{ij} \end{cases}, \quad A_{ji} = A_{ij}$$

for all $1 \leq i \leq j \leq n$.

Statistical graph theory often considers the case of unweighted graph, i.e., $W_{ij} = 1, \forall i,j$, for which (8) is called random graphs with independent edges [19]. Here, we require $A$ to be weighted to model the network coupling strength. One key result for such an independent edge model is that for large networks, the random adjacency matrix $A$ does not deviate from its expected value $E.A$ too much, with high probability. Further, such concentration result can be extended for the Laplacian matrix $L_A$ as well.
Proposition 3. Suppose \( \max_{i,j} |W_{ij}| \leq 1 \). Let \( \Delta := \max_i \sum_j P_{ij} W_{ij}^2 \). For any \( c > 0 \), if \( \Delta \geq 16(c + 1) \log n \), then for any \( 4n^{-c} \leq \delta < 1 \), we have
\[
P \left( \| L_A - L_{EA} \| \leq 8 \sqrt{\Delta \log(4n/\delta)} \right) \geq 1 - \delta.
\]

We refer the readers to the Appendix for the proof. We make the following remarks. Firstly, this result is a generalization of [19, Theorem 3.1]. Specifically, [19] considers the unweighted graph \( (W_{ij} = 1, \forall i, j) \) and derived concentration results on the normalized Laplacian \( D^{-1/2}L D^{-1/2} \), while our result works for weighted graph and provide the concentration result regarding the original Laplacian \( L \).

Within this family of random graphs, we consider the one with two coherent groups:

**Weighted Stochastic Block Model with Two Communities** \( (I_A, I_B, p, q, w_p, w_q) \): Given a partition \( (I_A, I_B) \) of \( [n] \), the adjacency matrix \( A \) is generated as in \( (3) \) with
\[
\begin{aligned}
P_{ij} &= p, W_{ij} = w_p, \quad \mathcal{I}^{-1}(i) = \mathcal{I}^{-1}(j) \quad \text{if } \mathcal{I}(i) = \mathcal{I}(j), \\
P_{ij} &= q, W_{ij} = w_q, \quad \mathcal{I}^{-1}(i) \neq \mathcal{I}^{-1}(j) \quad \text{otherwise},
\end{aligned}
\]

where \( \mathcal{I}^{-1}(i) = \{a, b; i \in I_A, b \in I_B \} \).

When \( w_p = w_q = 1 \), this is exactly the stochastic block model with two communities [18]. For the weighted version \( w_p, w_q \geq 0 \), notice that \( E_A = A_{bb} \) (up to a permutation matrix) with \( \alpha = pw_p, \beta = qw_q, n_a = |I_A|, n_b = |I_B| \). Then \( L_{EA} = L_{bb} \) is exactly the Laplacian matrix for the ideal network discussed in Section 3.1. Given that \( \| L_A - L_{EA} \| \) is small with high probability, we have the following result regarding the spectral properties of \( L_A \):

**Theorem 4.** Suppose \( 1 \geq p > q \geq 0, w_q = \gamma w_p \) with \( 0 < \gamma < 1 \). We let \( n_{\min} := \min \{|I_A|, |I_B|\} \) and \( n = |I_A| + |I_B| \).

If \( n_{\min} = \Omega(n) \), then given any \( 0 < \delta < 1 \) and large enough \( n \), with probability at least \( 1 - \delta \) the following holds:

1. Large third smallest eigenvalue:
\[
\lambda_3(L_A) \geq w_p(p + \gamma q)n_{\min} - 8w_p \sqrt{np \log(4n/\delta)} \quad (9)
\]
2. Approximately Good Invariant Subspace:
\[
\sin(v_2(L_A), v_2(L_{EA})) \leq \frac{16 \sqrt{2}}{p - \gamma q} \frac{\sqrt{np \log(4n/\delta)}}{n_{\min}^2}, \quad (10)
\]

where
\[
\sin(v_2(L_A), v_2(L_{EA})) = \sqrt{1 - \| v_2(L_A)^T v_2(L_{EA}) \|^2}.
\]

**Proof sketch.** With the upper bound \( \| L_A - L_{EA} \| \sim O_p(\sqrt{n \log n}) \) from Proposition 3. The first result is due to Weyl’s inequality [20], that is \( |\lambda_3(L_A) - \lambda_3(L_{EA})| \leq \| L_A - L_{EA} \| \). The second results is a direct result of a variant of Davis-Khan Theorem in [21], that is \( \sin(v_2(L_A), v_2(L_{EA})) \sim O_p \left( \frac{\| L_A - L_{EA} \|}{\lambda_3(L_{EA}) - \lambda_2(L_{EA})} \right) \). We refer the readers to the Appendix for the proof. □

For large networks, if the sizes of two coherent groups are balanced so that \( n_{\min} \sim \Omega_p(n) \). Then (9) implies \( \lambda_3(L_A) \sim \Omega_p(n) \), showing that \( T_{2}(s) \) will be a good approximation to \( T_{2\nu}(s) \), by Theorem 1. Also, (10) shows that \( \sin(v_2(L_A), v_2(L_{EA})) \sim O_p \left( \frac{\| L_A - L_{EA} \|}{\lambda_3(L_{EA}) - \lambda_2(L_{EA})} \right) \), hence the \( T_2(s) \) constructed from \( v_2(L_A) \) is close to the one constructed from \( v_2(L_{EA}) \), which is exactly the two-node model from Theorem 2. Therefore, we should expect Algorithm 2 to perform well for the weighted stochastic block model, even if one instance of such random graph appears much different than an ideal \( A_{bb} \) as it has much fewer edges.

V. **APPLICATION:** MODELING FREQUENCY RESPONSE IN POWER NETWORKS

The frequency response of synchronous generator (including grid-forming inverters) networks, linearized at its equilibrium point [22], can be modeled exactly as the network model in Fig 1 with \( f(s) = \frac{1}{s} \) and

\( u_i \): Disturbance in mechanical power at generator \( i \).
\( y_i \): Frequency of generator \( i \)
\( g_i(s) \): Generator dynamics

\[ L: \text{Sensitivity of power injection w.r.t. bus phase angles} \]

As for generator dynamics, we use the second-order model

\[ g_i(s) = \frac{1}{m_i s + d_i + \frac{r_i^{-1}}{\tau_i s + 1}}, \]  

(11)

where \( m_i \) is the inertia, \( d_i \) the damping, \( r_i^{-1} \) the droop coefficient, and \( \tau_i \) the turbine time constant of generator \( i \).

Remark. Aggregating generators with second-order dynamics do not return a \( \hat{g}_i(s) \) with the same order as a single generator if the turbine time constant \( \tau_i \) are different across generators, then one may need to utilize model reduction techniques such as balanced truncation [23] on \( \hat{g}_i(s) \), please refer to [14] for a detailed discussion. In the experiment, we do not do model reduction on \( \hat{g}_i(s) \).

A. Synthetic Case: Weighted Stochastic Block Model

We first validate our algorithm with a synthetic test case, where generator dynamics follows [11] and we randomly sample the inertia and damping independently as

\[ m_i \sim \text{Uniform}([0.05, 0.5]), d_i \sim \text{Uniform}([0.2, 0.5]) \]

\[ r_i \sim \text{Uniform}([5, 10]), \tau_i \sim \text{Uniform}([2, 10]) \]

The adjacency matrix \( A \) is sampled from our weighted stochastic block model \( (I_a, I_b, p, q, w_p, w_q) \) where \( n_a = [I_a] = 30, n_b = [I_b] = 20, p = 0.6, q = 0.1, w_p = 5, w_q = 0.5 \). We note that for spectral clustering, Algorithm [1] always achieves perfect clustering across multiple runs. With the generated network model, we inject a step disturbance \( u_2(t) = \chi(t) \) at the second node and plot the step response of \( T_{yu}(s) \) in Fig. 3, along with the response \( \hat{y}_a, \hat{y}_b \) of our approximate model \( T_2(s) \) from Algorithm 2.

There is a clear difference between the dynamical response of generators from group \( a \) and group \( b \), and the aggregate responses \( \hat{y}_a, \hat{y}_b \) capture such difference while providing a good approximation to the actual node responses. Due to space constraints, we only present the result of running Algorithm 2 on one instance of the randomly generated networks, but the results are consistent across multiple runs.

Our theorem suggests that if we increase \( p \), i.e., having more intra-group connection, then \( \lambda_3(I_A) \) increases, which makes our approximation model closer to the true network. Indeed, we run the same experiment with \( p = 0.9 \), we see a more coherent behavior in the network, as shown in Figure 4.

B. Test Case: IEEE 68-bus System

Lastly, we apply our algorithm to the IEEE 68-bus test system [24]. We first use Kron reduction to eliminate the load buses in the network [25] and apply our algorithm to the reduced network with only the generator buses. The spectral clustering result (from Algorithm 1) correctly identifies the two areas in the test system, one for NETS and one for NYPS and its adjacent areas.

We also inject a step disturbance \( \chi(t) \) to the second generator in the network and plot the response of \( T_{yu}(s) \) and \( T_2(s) \). While the responses appear less coherent than the synthetic case, our approximation still captures the average trend in each group. Notably, the approximation model captures the underdamped response of coherent group \( a \), when the disturbance is injected to group \( b \).

VI. CONCLUSION

In this paper, we propose a novel model-reduction methodology for large-scale dynamic networks, based on the recent frequency-domain characterization of coherent dynamics in networked systems. Our analysis shows that networks with two coherent groups/areas can be well approximated by two aggregate nodes dynamically interacting with each other, and our results are theoretically justified for networks with ideal block structures and networks with random graphs generated from a weighted stochastic block model. The numerical results align with our theoretical findings. We believe our analysis can be extended to networks with more than two coherent groups and designing algorithms to identify multiple coherent groups and modeling their interaction are interesting future research directions.

REFERENCES


Fig. 5: IEEE 68-bus test system [24]. Image credits to [26].

Fig. 6: IEEE 68-bus system (16 generators): Step Response of $T_{pu}(s)$ and $T_2(s)$ from algorithm [2] (Middle) Response shown for only group $a$, (Right) Response shown for only group $b$. The generator injected with step disturbance is in group $b$

APPENDIX

A. Proof of Theorem 7

Proof of Theorem 7 Firstly, we have

\[ T_{yu}(s_0) = (I_n + G(s_0)f(s_0)L)^{-1}G(s_0) \]
\[ = (G^{-1}(s_0) + f(s_0)L)^{-1} \]
\[ = V(V^TG^{-1}(s_0)V + f(s_0)\Lambda)^{-1}V^T, \]

where \( G^{-1}(s_0) = \text{diag}\{g_i^{-1}(s_0)\}, \ \Lambda = \text{diag}\{\lambda_i(L)\}, \text{ and } V = [v_1(L), v_2(L), \cdots, v_n(L)]. \)

Let \( H = V^T\text{diag}\{g_i^{-1}(s_0)\}V + f(s_0)\Lambda, \) then

\[ T_{yu}(s_0) = VH^{-1}V^T. \]

Then it is easy to see that

\[ \|T_{yu}(s_0) - T_2(s_0)\| = \left\| T(s_0) - V \begin{bmatrix} H_2^{-1} & 0 \\ V^T & 0 \end{bmatrix} V^T \right\| \]
\[ = \left\| V \left( H^{-1} - \begin{bmatrix} H_2^{-1} & 0 \\ 0 & 0 \end{bmatrix} \right) V^T \right\| \]
\[ = \left\| H^{-1} - \begin{bmatrix} H_2^{-1} & 0 \\ 0 & 0 \end{bmatrix} \right\|, \]

(12)

where the last equality comes from the fact that multiplying by a unitary matrix \( V \) preserves the spectral norm.

Let \( V_2 := \left[ \frac{4}{\sqrt{n}} \quad v_2(L) \right] \) and \( V_2^+ := [v_3(L) \cdots v_n(L)] \), we now write \( H \) in block matrix form:

\[ H = V^T \text{diag}\{g_i^{-1}(s_0)\}V + f(s_0)\Lambda \]
\[ = \begin{bmatrix} V_2^T \\ (V_2^+)^T \end{bmatrix} \text{diag}\{g_i^{-1}(s_0)\} \begin{bmatrix} V_2 & V_2^+ \end{bmatrix} + f(s_0)\Lambda \]
\[ = \begin{bmatrix} H_2 & V_2^T \text{diag}\{g_i^{-1}(s_0)\}V_2 \\ (V_2^+)^T \text{diag}\{g_i^{-1}(s_0)\}V_2 + f(s_0)\Lambda \end{bmatrix} \]
\[ := \begin{bmatrix} H_2 & H_2^T \\ H_o & H_d \end{bmatrix}, \]

where \( \hat{\Lambda} = \text{diag}\{\lambda_3(L), \cdots, \lambda_n(L)\}. \)

Inverting \( H \) in its block form, we have

\[ H^{-1} = \begin{bmatrix} A & -H_2^{-1}H_oA \\ -H^{-1}H_oA & H_o^{-1} + H_o^{-1}H_oAH_oH_d^{-1} \end{bmatrix}, \]

where \( a = (H_2 - H^T_oH_o^{-1}H_2)^{-1}. \)

Notice that \( \|V_2^+\| = 1 \) and \( \|V_2\| = 1, \) we have

\[ \|H_o\| = \|V_2^T \text{diag}\{g_i^{-1}(s_0)\}V_2\| \]
\[ \leq \|V_2\|\|\text{diag}\{g_i^{-1}(s_0)\}\|\|V_2\| \leq M_2. \]

(13)

Also, by Weyl’s inequality [20], when \( |f(s_0)|\lambda_2(L) > M_2, \) the following holds:

\[ \|H_d^{-1}\| = \|((f(s_0)\hat{\Lambda} + (V_2^+)^T \text{diag}\{g_i^{-1}(s_0)\}V_2^+)^{-1}\| \]
\[ \leq \frac{1}{\sigma_1(f(s_0)\hat{\Lambda}) - \|((V_2^+)^T \text{diag}\{g_i^{-1}(s_0)\}V_2^+)\|} \]
\[ \leq \frac{1}{\sigma_1(f(s_0)\hat{\Lambda}) - M_2} \leq \frac{1}{|f(s_0)|\lambda_3(L) - M_2}. \]

(14)

Lastly, when \( |f(s_0)|\lambda_2(L) > M_2 + M_3^2M_1, \) a similar reasoning as above, using (13) (14), and our assumption \( \|T_2(s_0)\| = \|H_2^{-1}\| \leq M_1, \) gives

\[ \|A\| \leq \frac{1}{\|H_o\| - \|H_oH_d^{-1}H_o\|} \]
\[ \leq \frac{1}{\|H_2\| - \|H_o\|^2\|H_d^{-1}\|} \]
\[
\frac{1}{M_1 - \frac{M_2^2}{|f(s_0)|\lambda_3(L) - M_2}} \leq \frac{M_1^2}{|f(s_0)|\lambda_3(L) - M_2 - M_1 M_2^2}.
\]  

Now we bound the norm of \( H^{-1} - \begin{bmatrix} H_2^{-1} & 0 \\ 0 & 0 \end{bmatrix} \) by the sum of norms of all its blocks:

\[
\left\| H^{-1} - \begin{bmatrix} H_2^{-1} & 0 \\ 0 & 0 \end{bmatrix} \right\| 
= \left\| \begin{bmatrix} A H_o^T H_o^{-1} H_o H_2 & -a H_o^T H_o^{-1} \\ -a H_o^{-1} H_o & H_o^{-1} + a H_o^{-1} H_o H_o^T H_o^{-1} \end{bmatrix} \right\| 
\leq \| A \| \| H_o^{-1} \| (\| H_2 \| \| H_o \|^2 + 2\| H_o \| + \| H_o \|^2 \| H_o^{-1} \|) 
+ \| H_o^{-1} \|, 
\]  

Using (13)-(14)-(15), we can further upper bound (16) as

\[
\left\| H^{-1} - \begin{bmatrix} H_2^{-1} & 0 \\ 0 & 0 \end{bmatrix} \right\| 
\leq \frac{M_1^2 M_2^2 + 2M_1 M_2 + \frac{M_1 M_2^2}{|f(s_0)|\lambda_3(L) - M_2} + 1}{|f(s_0)|\lambda_3(L) - M_2} \frac{1}{|f(s_0)|\lambda_3(L) - M_2 - M_1 M_2^2}.
\]  

This bound holds as long as \( |f(s_0)|\lambda_3(L) > M_2 + M_2^2 M_1 \). Combining (12) and (17) gives the desired inequality.  \( \square \)
B. Eigenvalues and Eigenvectors of $L_{\text{blk}}(n_a, n_b, \alpha, \beta)$

The matrix $A_{\text{blk}}(n_a, n_b, \alpha, \beta)$ is defined to be

$$A_{\text{blk}}(n_a, n_b, \alpha, \beta) = \begin{bmatrix} \alpha I_{n_a} & \beta I_{n_a} \\ \beta I_{n_a} & \alpha I_{n_b} \end{bmatrix},$$

and $L_{\text{blk}}(n_a, n_b, \alpha, \beta) = \text{diag}\{A_{\text{blk}}1_{n_a+n_b}\} - A_{\text{blk}}$.

Consider any non-zero vector $v$ such that $L_{\text{blk}}v = \lambda v$ for some $\lambda \geq 0$. We write $v = \begin{bmatrix} v_{1:n_a} \\ v_{n_a+1:n_b} \end{bmatrix} := \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$. Then $L_{\text{blk}}v = \lambda v$ can be written as

$$\begin{bmatrix} (n_a\alpha + n_b\beta)v_1 \\ (n_b\alpha + n_a\beta)v_2 \end{bmatrix} - \begin{bmatrix} (n_a\alpha (I_{n_a}^T v_1) + n_b\beta (I_{n_b}^T v_2)) I_{n_a} \\ (n_b\alpha (I_{n_b}^T v_2) + n_a\beta (I_{n_a}^T v_1)) I_{n_b} \end{bmatrix} = \lambda \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}.$$

(18)

Multiply $\begin{bmatrix} I_{n_a}^T & 0 \\ 0 & I_{n_b} \end{bmatrix}$ to the left of (18), we have

$$\begin{bmatrix} (n_a\alpha + n_b\beta(T_{n_a} v_1) \\ (n_b\alpha + n_a\beta(v_2) \end{bmatrix} - \begin{bmatrix} (n_a\alpha (I_{n_a}^T v_1) + n_b\beta (I_{n_b}^T v_2)) I_{n_a} \\ (n_b\alpha (I_{n_b}^T v_2) + n_a\beta (I_{n_a}^T v_1)) I_{n_b} \end{bmatrix} = \lambda \begin{bmatrix} (I_{n_a}^T v_1) \\ (I_{n_b}^T v_2) \end{bmatrix},$$

which leads to

$$\begin{bmatrix} n_b\beta - \lambda \\ -n_b\beta \end{bmatrix} = \lambda \begin{bmatrix} n_a\beta - \lambda \\ -n_a\beta \end{bmatrix}.$$

We view the equation above as a system of linear equations:

**When it has non-zero solution** $\begin{bmatrix} (I_{n_a}^T v_1) \\ (I_{n_b}^T v_2) \end{bmatrix} \neq 0$: It implies det $\begin{bmatrix} n_b\beta - \lambda & -n_a\beta \\ -n_b\beta & n_a\beta - \lambda \end{bmatrix} = 0$, which is $\lambda(\lambda - (n_a+n_b)\beta) = 0$.

Therefore $\lambda = 0$ or $\lambda = (n_a + n_b)\beta$, this gives two eigenpair:

$$\left( \lambda = 0, v = \frac{1}{\sqrt{n}} \mathbf{1}_{n_a} \right), \text{ or } \left( \lambda = (n_a + n_b)\beta, v = \frac{1}{\sqrt{n}} \begin{bmatrix} \frac{n_b}{n_a} \\ -\frac{n_a}{n_b} \end{bmatrix} \right),$$

where $n = n_a + n_b$, and eigenvector $v$ is normalized, i.e., $\|v\| = 1$.

**When it has only zero solution** $\begin{bmatrix} (I_{n_a}^T v_1) \\ (I_{n_b}^T v_2) \end{bmatrix} = 0$: When both $(I_{n_a}^T v_1), (I_{n_b}^T v_2)$ are zero, (18) reduces to

$$\begin{bmatrix} (n_a\alpha + n_b\beta)v_1 \\ (n_b\alpha + n_a\beta)v_2 \end{bmatrix} = \lambda \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}.$$

When either $n_a = n_b$ or $\alpha = \beta$, one have $n_a\alpha + n_b\beta = n_b\alpha + n_a\beta = \lambda$. This is an simple eigenvalue with algebraic multiplicity $n_a + n_b - 2$.

When $n_a \neq n_b$ and $\alpha \neq \beta$, we have $n_a\alpha + n_b\beta \neq n_b\alpha + n_a\beta$. In this case, $v_1$ and $v_2$ can not be non-zero at the same time and

1) $\left( \lambda = n_a\alpha + n_b\beta, v = \begin{bmatrix} v_1 \\ 0 \end{bmatrix} \right)$ is an eigenpair for any $v_1$ such that $x_{n_a}^T v_1 = 0$, $\|v_1\| = 1$.

2) $\left( \lambda = n_b\alpha + n_a\beta, v = \begin{bmatrix} 0 \\ v_2 \end{bmatrix} \right)$ is an eigenpair for any $v_2$ such that $x_{n_b}^T v_2 = 0$, $\|v_2\| = 1$.

Then $\lambda = n_a\alpha + n_b\beta$ is an simple eigenvalue with algebraic eigenvalue $n_a - 1$ and so is $\lambda = n_b\alpha + n_a\beta$ with algebraic eigenvalue $n_b - 1$.

So far we find all eigenvalues and eigenvectors of $L_{\text{blk}}$.

Notice that when $\alpha \geq \beta$, we have $\min\{n_a\alpha + n_b\beta, n_b\alpha + n_a\beta\} \geq (n_a + n_b)\beta$. In this case, the first two smallest eigenvalues and their corresponding eigenvectors are

$$\begin{bmatrix} \lambda_1(L_{\text{blk}}) = 0, v_1(L_{\text{blk}}) = \frac{1}{\sqrt{n}} \mathbf{1}_{n_a} \end{bmatrix}, \text{ or } \begin{bmatrix} \lambda_2(L_{\text{blk}}) = (n_a + n_b)\beta, v_2(L_{\text{blk}}) = \frac{1}{\sqrt{n}} \begin{bmatrix} \frac{n_b}{n_a} \\ -\frac{n_a}{n_b} \end{bmatrix} \end{bmatrix}.$$

and $\lambda_3(L_{\text{blk}}) = \min\{n_a\alpha + n_b\beta, n_b\alpha + n_a\beta\}$. 
C. Proofs of Theorem 2

Proof of Theorem 2

Since $\nu_2(L_{bik}) = \frac{1}{\sqrt{n}} \left[ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \right]$, we have

$$T_2(s) = \frac{1}{n} \left[ \mathbb{1}_{n_a} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} - \mathbb{1}_{n_b} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \right] H_2^{-1} \left[ \mathbb{1}_{n_a} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} - \mathbb{1}_{n_b} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \right]^T,$$

where

$$H_2(s) = \left[ \begin{array}{cc} \frac{1}{n} \left( \hat{g}_{a}^{-1}(s) + \hat{g}_{b}^{-1}(s) \right) & \frac{1}{n} \left( \frac{n_a}{n_a} \hat{g}_{a}^{-1}(s) - \frac{n_a}{n_b} \hat{g}_{b}^{-1}(s) \right) \\ \frac{1}{n} \left( \frac{n_a}{n_a} \hat{g}_{a}^{-1}(s) - \frac{n_a}{n_b} \hat{g}_{b}^{-1}(s) \right) & \frac{1}{n} \left( \frac{n_a}{n_a} \hat{g}_{a}^{-1}(s) + \frac{n_a}{n_a} \hat{g}_{b}^{-1}(s) + \lambda_2(L_{bik}) f(s) \right) \end{array} \right],$$

Notice that

$$\left[ \begin{array}{cc} \mathbb{1}_{n_a} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \\ \mathbb{1}_{n_b} - \mathbb{1}_{n_b} \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \end{array} \right] \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right] = \left[ \begin{array}{cc} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ 0 \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right].$$

Then

$$T_2(s) = \left[ \begin{array}{cc} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ 0 \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right] \frac{1}{n} \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^{-1} H_2^{-1}(s) \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^{-T} \left[ \begin{array}{cc} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ 0 \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^T.$$

Now

$$\frac{1}{n} \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^{-1} H_2^{-1}(s) \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^{-T} = \left( \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right)^T H_2(s) \left[ \begin{array}{cc} \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_a} \mathbb{1}_{n_a} - \sqrt{\frac{n_a}{n_a}} \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^{-1}$$

$$= \left( \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \hat{g}_{a}^{-1}(s) \right) \left( \frac{n_a}{n_a} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \hat{g}_{b}^{-1}(s) \right) + \lambda_2(L_{bik}) \frac{n_a n_b}{n} \left[ \begin{array}{cc} 1 & -1 \\ -1 & 1 \end{array} \right] f(s) \left[ \begin{array}{cc} 1 & -1 \\ -1 & 1 \end{array} \right]^{-1}$$

$$= (\hat{G}^{-1}(s) + \hat{L} f(s))^{-1}$$

$$= (I_2 + \hat{G}(s) \hat{L} f(s))^{-1} \hat{G}(s) := \hat{T}_2(s).$$

Therefore $T_2(s) = \left[ \begin{array}{cc} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ 0 \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right] \hat{T}_2(s) \left[ \begin{array}{cc} \mathbb{1}_{n_a} \mathbb{1}_{n_a} \\ 0 \mathbb{1}_{n_b} \mathbb{1}_{n_b} \end{array} \right]^T$, where $\hat{T}_2(s)$ is exactly a network model with two nodes.
D. Proofs for Section IV

Lemma 5 (Corollary 7.1 in [19]). Let $X_1, \ldots, X_n$ be mean-zero independent random $d \times d$ Hermitian matrices and such that there exists a $M > 0$ with $\|X_i\| \leq M$ almost surely for $1 \leq i \leq n$. Define $\sigma^2 \equiv \lambda_{\max} (\sum_{i=1}^{n} \mathbb{E}[X_i^2])$. Then for all $t > 0$,

$$
P \left( \left\| \sum_{i=1}^{n} X_i \right\| \geq t \right) \leq 2d \exp \left( - \frac{t^2}{8 \sigma^2 + 4Mt} \right).
$$

Lemma 6 (Direct consequence of Theorem 3.3 in [27]). Let $X_1, \ldots, X_n$ be independent Bernoulli random variables with $P (X_i = 1) = p_i, 1 \leq i \leq n$. For $X = \sum_{i=1}^{n} a_i X_i$ with $a_i > 0$, we define $\nu = \sum_{i=1}^{n} a_i^2 p_i$. Then, we have

$$
P (\|X - \mathbb{E}[X]\| \geq t) \leq \exp \left( - \frac{t^2}{2(\nu + a_{\max} t/3)} \right),
$$

where $a_{\max} = \max_i a_i$.

Proof of Proposition 3. We let $W = [W_{ij}], P = [P_{ij}]$, where $W_{ji} = W_{ij}, P_{ji} = P_{ij}, \forall j > i$. Notice that $\mathbb{E}A = W \odot P$.

Since $L_A = D_A - A$ with $D_A = \text{diag}\{A1\}$, we have

$$
L_A - L_{W \odot P} = D_A - A - D_{W \odot P} - W \odot P.
$$

Therefore,

$$
P (\|L_A - L_{W \odot P}\| \geq t)
= P (\|D_A - A - D_{W \odot P} - W \odot P\| \geq t)
\leq P (\|D_A - D_{W \odot P}\| + \|A - W \odot P\| \geq t)
\leq P (\|D_A - D_{W \odot P}\| \geq t/2) + P (\|A - W \odot P\| \geq t/2).
$$

We need to upper bound each term separately (We define $\Delta := \max_i \sum_{j=1}^{n} P_{ij} W_{ij}^2$):

Upper bound for $P (\|D_A - D_{W \odot P}\| \geq t/2)$:

For the first term, notice that both $D_A, D_{W \odot P}$ are diagonal, we have

$$
P (\|D_A - D_{W \odot P}\| \geq t/2)
= P \left( \max_i |[D_A]_{ii} - [D_{W \odot P}]_{ii}| \geq \frac{t}{2} \right)
\leq \sum_{i=1}^{n} P \left( |[D_A]_{ii} - [D_{W \odot P}]_{ii}| \geq \frac{t}{2} \right)
\leq \sum_{i=1}^{n} P \left( \left| \sum_j A_{ij} - \sum_j W_{ij} P_{ij} \right| \geq \frac{t}{2} \right)
\leq \sum_{i=1}^{n} 2 \exp \left( - \frac{\frac{t^2}{8 (\sum_{j=1}^{n} P_{ij} W_{ij}^2 + t/6)} \right)
\leq 2n \exp \left( - \frac{t^2}{8(\Delta + t/6)} \right).
$$

Upper bound for $P (\|A - W \odot P\| \geq t/2)$:

For the second term, let $e_i \in \mathbb{R}^n$ be the $i$-th column of the identity matrix $I_n$. Then

$$
A - W \odot P = \sum_{1 \leq i \leq j \leq n} X_{ij}, \text{where } X_{ij} = \begin{cases} (A_{ij} - W_{ij} P_{ij})(e_i e_j^T + e_j e_i^T), & i \neq j \\ (A_{ij} - W_{ij} P_{ij}) e_i e_i^T, & i = j \end{cases}.
$$

Notice that $X_{ij}, 1 \leq i \leq j \leq n$ are mean-zero ($\mathbb{E}[A_{ij}] = W_{ij} P_{ij}$), Hermitian, and we have $\|X_{ij}\| \leq 1, i \leq j \leq n$ almost surely. To apply Lemma 5 we need to compute $\| \sum_{1 \leq i \leq j \leq n} \mathbb{E}[X_{ij}^2] \|$. Since

$$
\mathbb{E}[X_{ij}^2] = \begin{cases} (1 - P_{ij}) P_{ij} W_{ij}^2 (e_i e_i^T + e_j e_j^T), & i \neq j \\ (1 - P_{ij}) P_{ij} W_{ij}^2 e_i e_i^T, & i = j \end{cases},
$$

we have

$$
\sum_{1 \leq i \leq j \leq n} \mathbb{E}[X_{ij}^2] = \sum_{i=1}^{n} \left( \sum_{j=1}^{n} (1 - P_{ij}) P_{ij} W_{ij}^2 \right) e_i e_i^T.
$$
Therefore $\sum_{1 \leq i \leq j \leq n} \mathbb{E}[X_{ij}^2]$ is a diagonal matrix with each diagonal entry upper bounded by
\[
\max_i \left( \sum_{j=1}^n (1 - P_{ij}) P_{ij} W_{ij}^2 \right) \leq \max_i \sum_{j=1}^n P_{ij} W_{ij}^2 := \Delta .
\]
Invoke Lemma 5 to obtain
\[
\mathbb{P}(\|A - W \odot P\| \geq t/2) \leq 2n \exp\left(-\frac{t^2}{32\Delta + 16t}\right), \forall t \geq 0
\]
Combining the two upper bounds:
Overall, we have
\[
\mathbb{P}(\|L_A - LW \odot P\| \geq t) \\
\leq \mathbb{P}(\|D_A - DW \odot P\| \geq t/2) + \mathbb{P}(\|A - W \odot P\| \geq t/2) \\
\leq 2n \exp\left(-\frac{t^2}{8(\Delta + t/6)}\right) + 2n \exp\left(-\frac{t^2}{32\Delta + 16t}\right) \\
\leq 4n \exp\left(-\frac{t^2}{32\Delta + 16t}\right).
\]
Now set $t = 8\sqrt{\Delta \log(4n/\delta)}$, the assumption $\Delta \geq 16(c + 1)\log n$ implies $t \leq 2\Delta$. Therefore,
\[
4n \exp\left(-\frac{t^2}{32\Delta + 16t}\right) \leq 4n \exp\left(-\frac{t^2}{64\Delta}\right) = \delta.
\]
This leads to exactly
\[
\mathbb{P}(\|L_A - LW \odot P\| \leq 8\sqrt{\Delta \log(4n/\delta)}) \geq 1 - \delta.
\]
Recall that $\mathbb{E}A = W \odot P$, we have the desired result. \hfill \(\square\)

**Proof of Theorem 4.** For the random matrix $A$ generated by the weighted stochastic block model $(I_a, I_b, p, q, w_p, w_q)$, we have
\[
\Delta = \max_i \sum_j P_{ij} W_{ij}^2 = \max\{n_a p w_p^2, n_b q w_q^2\} \leq n p w_p^2,
\]
and
\[
\Delta = \max\{n_a p w_p^2, n_b q w_q^2\} \geq n \min \{q w_q^2\}.
\]
Therefore, for any $0 < \delta < 1$, pick $c > 0$ and $n$ sufficiently large such that $n^{-c} \leq \delta$ and $\Delta \geq 16(c + 1)\log n$. The latter is possible since $n \min = \Omega(n)$, so that sufficient large $n$ has
\[
\Delta \geq n \min q w_q^2 \geq 16(c + 1)\log n.
\]
By Proposition 3, we have, with probability $1 - \delta$,
\[
\|L_A - L_{E_A}\| \leq 8\sqrt{\Delta \log(4n/\delta)} \leq 8w_p \sqrt{n p \log(4n/\delta)} .
\]
(19)

Given the event (19), by Weyl’s inequality [20, Theorem 4.3.1], we have
\[
\lambda_3(L_{E_A}) - \lambda_3(L_A) \leq \|L_A - L_{E_A}\| \leq 8w_p \sqrt{n p \log(4n/\delta)}.
\]
Following the analysis in Appendix B we know $\lambda_3(L_{E_A}) = \min\{n_a p w_p + n_b q w_q, n_b p w_p + n_a q w_q\} \geq \min (p + q) w_p$, then
\[
\lambda_3(L_A) \geq \lambda_3(L_{E_A}) - 8w_p \sqrt{n p \log(4n/\delta)} \geq \min (p + q) w_p - 8w_p \sqrt{n p \log(4n/\delta)}.
\]
This proves the first inequality. For the second inequality, by [Theorem 2] [21], we have
\[
\|\sin \Theta(\hat{V}, V)\|_F \leq \frac{2\sqrt{2} \|L_A - L_{E_A}\|}{\lambda_3(L_{E_A}) - \lambda_2(L_{E_A})},
\]
where $\hat{V} = \left[\begin{array}{c} \frac{v_1}{\sqrt{n}} \\ \frac{v_2}{\sqrt{n}} \end{array}\right] v_2(L_A)$ and $V = \left[\begin{array}{c} \frac{v_1}{\sqrt{n}} \\ \frac{v_2}{\sqrt{n}} \end{array}\right] v_2(L_{E_A})$, and the matrix $\sin \Theta(\hat{V}, V)$ is a diagonal matrix of $\sqrt{1 - \sigma_1^2(V^T \hat{V})}$. Notice that $\sigma_1(V^T \hat{V}) = 1$ and $\sigma_2(V^T \hat{V}) = v_2^2(L_{E_A})$, then
\[
\|\sin \Theta(\hat{V}, V)\|_F = \sin(v_2(L_A), v_2(L_{E_A})) \leq \frac{2\sqrt{2} \|L_A - L_{E_A}\|}{\lambda_3(L_{E_A}) - \lambda_2(L_{E_A})} = \frac{2\sqrt{2} \|L_A - L_{E_A}\|}{\min w_p (p - q)} \leq \frac{16\sqrt{2} w_p \sqrt{n p \log(4n/\delta)}}{n \min w_p (p - q)},
\]
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which is exactly the desired inequality

\[
\sin(v_2(L_A), v_2(L_{EA})) \leq \frac{16\sqrt{2}}{w_p(p - \gamma q)} \sqrt{\frac{np \log(4n/\delta)}{n_{\text{min}}^2}}.
\]