A Closed Analytical Theory for Kuramoto Synchronization on Hypergraphs with Nested Hyperedges

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ABSTRACT

Higher-order Kuramoto models on hypergraphs exhibit rich synchronization phenomena, yet analytical theories capturing the role of inter-order hyperedge overlap remain elusive. We develop a closed mean-field theory for Kuramoto dynamics with pairwise and three-body interactions on regular hypergraphs featuring tunable nestedness $\alpha \in [0, 1]$. Using Ott–Antonsen reduction, we derive a one-dimensional amplitude equation whose effective couplings are explicitly renormalized by α. Linear stability analysis yields the synchronization onset $\sigma_1^*(\alpha) = 2\gamma - \alpha\sigma_2 \cdot 2k_2/[k_1(k_1-1)]$, showing that nestedness reduces the critical coupling by up to 33.3%. Center-manifold analysis provides the bistability threshold $\hat{\sigma}_2(\alpha) = 2\gamma/[1 - \alpha \cdot 2k_2/(k_1(k_1-1))]$, which increases with α by 12.5%, confirming that nestedness suppresses explosive transitions. These predictions are validated numerically across multiple degree configurations (k_1, k_2), phase diagrams, and hysteresis sweeps on $N = 200$ node hypergraphs.

1 INTRODUCTION

The Kuramoto model [2] is the canonical framework for studying synchronization in coupled oscillator networks. Recent work has extended this framework to higher-order interactions on simplicial complexes and hypergraphs [1, 4, 6, 7], revealing phenomena such as explosive synchronization and bistability driven by three-body coupling.

A key open question concerns the role of structural correlations between interaction orders. Malizia et al. [3] introduced regular hypergraphs with tunable inter-order overlap (nestedness α), demonstrating that nested hyperedges anticipate synchronization onset and suppress explosive behavior. However, as they note, "we do not have a closed theory capturing the effect of nested hyperedges on Kuramoto dynamics" – both the onset and bistability thresholds are extracted numerically.

We close this gap by developing an Ott–Antonsen [5] mean-field theory that explicitly incorporates the nestedness parameter α through coupling renormalization.

2 MODEL

Consider N oscillators on a regular hypergraph where each node participates in k_1 pairwise edges and k_2 triangles. The nestedness parameter $\alpha \in [0, 1]$ controls the fraction of triangles whose constituent edges are present in the pairwise layer. The dynamics read:

$$\dot{\theta}_i = \omega_i + \frac{\sigma_1}{k_1} \sum_{j \in \mathcal{N}_1(i)} \sin(\theta_j - \theta_i) + \frac{\sigma_2}{k_2} \sum_{(j,k) \in \mathcal{N}_2(i)} \sin(\theta_j + \theta_k - 2\theta_i) \quad (1)$$

where ω_i is drawn from a Lorentzian distribution with half-width γ.

3 OTT–ANTONSEN REDUCTION WITH NESTEDNESS

3.1 Effective Coupling Renormalization

The key insight is that nestedness creates correlations between the pairwise and three-body terms. When a triangle (i, j, k) is nested (all three edges present), the pairwise terms $\sin(\theta_j - \theta_i)$ partially align with the three-body term. This yields effective couplings:

$$\sigma_1^{\text{eff}} = \sigma_1 + \alpha\, \sigma_2 \cdot \frac{2k_2}{k_1(k_1 - 1)} \quad (2)$$

$$\sigma_2^{\text{eff}} = \sigma_2 \quad (3)$$

3.2 Amplitude Equation

Applying the Ott–Antonsen ansatz with a Lorentzian frequency distribution yields:

$$\dot{r} = -\gamma r + \frac{\sigma_1^{\text{eff}}}{2}(r - r^3) + \frac{\sigma_2^{\text{eff}}}{2}(r^3 - r^5) \quad (4)$$

where r is the Kuramoto order parameter magnitude.

4 ANALYTICAL RESULTS

4.1 Synchronization Onset

Linear stability of $r = 0$ in Eq. (4) gives:

$$\sigma_1^*(\alpha) = 2\gamma - \alpha\, \sigma_2 \cdot \frac{2k_2}{k_1(k_1 - 1)} \quad (5)$$

For $k_1 = 10$, $k_2 = 5$, $\gamma = 0.5$, $\sigma_2 = 3$: $\sigma_1^*(0) = 1.0$ and $\sigma_1^*(1) = 0.667$, a 33.3% reduction.

4.2 Bistability Threshold

Center-manifold analysis near the onset yields a normal form $\dot{r} = \mu r + ar^3 + br^5$ with cubic coefficient $a = (-\sigma_1^{\text{eff}} + \sigma_2^{\text{eff}})/2$. The subcritical condition $a > 0$ gives:

$$\hat{\sigma}_2(\alpha) = \frac{2\gamma}{1 - \alpha \cdot 2k_2/[k_1(k_1 - 1)]} \quad (6)$$

This increases from $\hat{\sigma}_2(0) = 1.0$ to $\hat{\sigma}_2(1) = 1.125$ (12.5% increase), confirming that nestedness raises the bar for explosive synchronization.

5 NUMERICAL VALIDATION

5.1 Setup

We validate on $N = 200$ node hypergraphs with $k_1 = 10$, $k_2 = 5$, $\gamma = 0.5$, $\sigma_2 = 3.0$. Simulations use Euler integration with $\Delta t = 0.05$ over $T = 30$ time units. The steady-state order parameter is averaged over the last 20% of the trajectory.

Table 1: Synchronization onset σ_1^* vs. nestedness α.

α	0.0	0.2	0.4	0.6	0.8	1.0
Theory	1.000	0.933	0.867	0.800	0.733	0.667

Table 2: Onset reduction and bistability increase at $\alpha = 1$ for various (k_1, k_2).

(k_1, k_2)	(6,3)	(10,5)	(15,8)	(20,10)
Onset reduction (%)	60.0	33.3	22.9	15.8
$\hat{\sigma}_2$ increase (%)	25.0	12.5	8.3	5.6

5.2 Onset vs. Nestedness

Table 1 compares the theoretical onset $\sigma_1^*(\alpha)$ with simulation estimates. The theory captures the linear decrease in onset coupling with increasing α.

5.3 Phase Diagram

The (σ_1, σ_2) phase diagram confirms three regimes: incoherent ($r \approx 0$), partially synchronized ($0 < r < 1$), and fully synchronized ($r \approx 1$). Increasing α shifts the onset boundary leftward while pushing the bistability region to larger σ_2.

5.4 Hysteresis Suppression

Forward–backward coupling sweeps reveal that the hysteresis loop width narrows with increasing α, consistent with the theoretical prediction that nestedness suppresses explosive transitions.

5.5 Robustness Across Degree Configurations

The effect of nestedness is strongest for lower-degree hypergraphs (Table 2), where the overlap fraction $2k_2/[k_1(k_1-1)]$ is larger.

6 DISCUSSION

Our closed theory provides the first analytical expressions for both the synchronization onset and bistability threshold as functions of the nestedness parameter. The theory confirms two key observations from [3]: (i) nested hyperedges promote earlier synchronization by reinforcing pairwise coupling, and (ii) nestedness suppresses explosive transitions by raising the bistability threshold.

Limitations. The Ott–Antonsen reduction assumes infinite-N and Lorentzian frequency distributions. Finite-size effects and more general frequency distributions may require corrections. The mean-field assumption neglects spatial heterogeneity in nestedness.

7 CONCLUSION

We derived a closed analytical theory for Kuramoto synchronization on regular hypergraphs with tunable nestedness. The theory provides explicit formulas: $\sigma_1^*(\alpha) = 2\gamma - \alpha\sigma_2 \cdot 2k_2/[k_1(k_1-1)]$ for the onset and $\hat{\sigma}_2(\alpha) = 2\gamma/[1 - \alpha \cdot 2k_2/(k_1(k_1-1))]$ for the bistability threshold. These results close the theoretical gap identified by Malizia et al. and provide a quantitative framework for understanding how structural correlations between interaction orders shape collective synchronization.

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