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Analysis of the Heterogeneous Vectorial Network Model of Collective Motion

Jalil Hasanyan, Lorenzo Zino, Agnieszka Truszkowska, Alessandro Rizzo, *Senior Member, IEEE*, and Maurizio Porfiri, *Fellow, IEEE*

Abstract—We analyze the vectorial network model, a stochastic protocol that describes collective motion of groups of agents, randomly mixing in a planar space. Motivated by biological and technical applications, we focus on a heterogeneous form of the model, where agents have different propensities to interact with others. By linearizing the dynamics about a synchronous state and leveraging an eigenvalue perturbation argument, we establish a closed-form expression for the mean-square convergence rate to the synchronous state in the absence of additive noise. These closed-form findings are extended to study the effect of added noise on the agents' coordination, captured by the polarization of the group. Our results reveal that heterogeneity has a detrimental effect on both the convergence rate and the polarization, which is nonlinearly moderated by the average number of connections in the group. Numerical simulations are provided to support our theoretical findings.

Index Terms—Stochastic systems; Stability of linear systems; Time-varying systems

I. INTRODUCTION

COLLECTIVE motion is a widely studied phenomenon across biology, physics, and engineering [1]–[3]. The emergence of collective motion is often observed in animal groups, such as bird flocks, fish schools, and sheep herds. Social animals have been shown to use locally controlled interactions for decision-making that ultimately regulate their coordination [1]. To capture these dynamics and better understand the emergence of coordination, the physics community has established a wide range of mathematical models of collective motion for groups of particles [2]. In the engineering community, the observations of spontaneous coordination of biological systems and the mathematical models developed by physicists have inspired the design and analysis of decentralized control schemes for teams of autonomous robots [3].

The vectorial network model (VNM), originally proposed by [4], [5], has emerged as a valuable paradigm to describe collective motion, for its mathematical tractability and ability

to reproduce important features of more complex models. In the VNM, each agent is characterized by its orientation on a planar space. Agents interact through a stochastically switching network, through which they dynamically update their orientation to synchronize with their neighbors. Such a dynamic updating is affected by intrinsic noise. The VNM has been initially proposed as a proxy of the classical Vicsek model for self-propelled systems [6], whose complexity restricted its analysis to numerical simulations [7]–[10] or case-specific theoretical results [11]–[15]. In the limit of rapidly moving particles, the VNM can capture several features of the richer Vicsek model [4], [5], [16].

The first analyses of the VNM were performed in the thermodynamic limit of large-scale systems, through extensive numerical simulations [4] and semi-analytical approaches [5]. These studies demonstrated the existence of a continuous order-disorder phase transition, similar to the Vicsek model in the case of rapidly moving particles that randomly mix at every time step [6]. For small values of added noise, the agents are successful in coordinating their motion. The extent of such a coordination smoothly decreases as the noise increases, until reaching completely disordered states when the level of noise is above a critical value. Further insight into the nature of the phase transition and its dependence on system parameters can be found in [16], where a mean-field theory of the VNM is developed and analytically investigated.

In [17], the VNM is analyzed without relying on the thermodynamic limit, via a linearization process that allows the VNM to be studied through the lens of consensus protocols [18], [19] — specifically, stochastic protocols on switching topologies [20] and with additive noise [21]. This linear analysis begot an array of closed-form results for homogeneous groups of agents, that is, where agents are indistinguishable in their ability to form connections with other group members. These results helped elucidate the effect of the population size, the number of connections of each agent, and noise on the coordination of the VNM. Further studies on the linearized VNM have shed light on various aspects of the collective dynamics, such as the effect of leader-follower interactions [22] and of specific choices of the noise inspired by biological applications [23].

All these analyses are based on the assumption that all the agents interact with the same number of individuals. Such an assumption is not reflective on many real-world complex systems. For instance, heterogeneity between the members of a group is a typical feature of animal groups [24] and complex coordination schemes between autonomous robots often

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involve the cooperation of different models or generations of robots [25]. Heterogeneity, indeed, has been shown to play a key, nontrivial role in many coordination processes. On the one hand, heterogeneous distribution of network connectivity hinders network synchronization in small-world networks [26] and convergence of stochastic consensus protocols [27]. On the other hand, the emergence of ordered states in complex networks may be favored by heterogeneous coupling [28] and heterogeneity may facilitate convergence of stochastic consensus protocols in the presence of leader-follower interactions [29]. To the best of our knowledge, there is still a gap in the theoretical understanding of the role of heterogeneity in the VNM. Filling this gap is expected to bring insight into collective motion of more complex models, thereby informing the design of coordination strategies for engineering systems and the understanding of real-world complex systems.

To this end, we examine the VNM in the general case where each agent is characterized by a different propensity to form time-varying, stochastic connections with other group members. Similar to [17], we rely on a linearization of the VNM about a synchronous state, and we present a toolbox of analytical results that capture the effect of heterogeneity on the asymptotic behavior of the VNM. First, through stochastic stability theory and eigenvalue perturbation methods, we establish closed-form results for the asymptotic convergence factor, which determines the convergence rate in the absence of noise. Our findings suggest that convergence to synchronous states is hindered by the heterogeneity of the agents' attitude to interact with others, at least for moderate levels of heterogeneity. In agreement with our intuition, this detrimental effect is moderated by the number of connections, where synchronization in denser networks is more robust to the effect of heterogeneity. Second, we study the polarization of the system [4], which is a global observable that quantifies the level of coordination between the agents. Following [17] and leveraging a perturbation argument, we derive a closed-form approximation for the polarization, which is exact in the small noise limit. Such an expression corroborates our previous finding, confirming that heterogeneity is detrimental for the emergence of ordered states, not only by slowing down the convergence, but also by decreasing the level of coordination of the system. Monte Carlo numerical simulations are provided to validate our analytical findings.

II. PROBLEM STATEMENT

A. Notation

The set of real numbers and nonnegative integers are represented by \mathbb{R} and \mathbb{Z}^+ , respectively. Given a vector \mathbf{x} , we denote its transpose by \mathbf{x}^\top . The N -dimensional all-1 (or 0) vector is denoted as $\mathbf{1}$ (or $\mathbf{0}$), and the N -dimensional identity matrix by I . The Euclidean norm of a vector is indicated by $\|\cdot\|$, the vectorization of a matrix by $\text{vec}(\cdot)$, the argument of a complex number by $\text{Angle}\{\cdot\}$, the expectation and the variance of a random variable by $\mathbb{E}[\cdot]$ and $\text{var}[\cdot]$, respectively. Matrix operations denoted by \otimes and \oslash are the Kronecker product and the Hadamard division, respectively. The spectral radius of a matrix is indicated by $\rho(\cdot)$. We use

Landau's symbol $O(x^k)$ for a generic function $f(\cdot)$ such that $\limsup_{x \rightarrow 0} \|f(x)/x^k\| < \infty$.

B. Heterogeneous VNM

We consider a system of N agents. Agent $i \in \{1, \dots, N\}$ is associated with the two-dimensional, unit-length vector $v_i = e^{i\theta_i}$ with i being the imaginary unit. With reference to the Vicsek model [6], the vector represents the heading direction of the particle. Each vector v_i updates its orientation θ_i according to a discrete-time process, as a consequence of interactions with other vectors. Agents are heterogeneous in their attitude to interact with others. Specifically, each agent i is characterized by a constant $a_i \in \mathbb{Z}^+$ that measures the number of interactions that agent i establishes at each time-step. These constants are gathered in the *interaction vector* \mathbf{a} . Similar to [27], we express the interaction vector as $\mathbf{a} = K\mathbf{1} + \sigma\mathbf{h}$, where

$$K := \frac{1}{N} \sum_{i=1}^N a_i \quad \text{and} \quad \sigma := \sqrt{\frac{1}{N} \sum_{i=1}^N (a_i - K)^2}, \quad (1)$$

are the average number of interactions and its standard deviation, respectively. Vector $\mathbf{h} \in \mathbb{R}^N$ (which is uniquely determined by vector \mathbf{a} , being $h_i = (a_i - K)/\sigma$) captures the deviations from the average number of connections and is such that $\mathbf{1}^\top \mathbf{h} = 0$, and $\|\mathbf{h}\| = \sqrt{N}$. In the original formulation of the VNM [4], [5], agents have homogeneous propensities of interaction, that is, for $a_i = K$, for $i = 1, \dots, N$.

At each time-step $k \in \mathbb{Z}^+$, agent i connects with a_i agents, chosen at random, independent of one another. Such a stochastic mechanism induces a switching topology — a growingly popular research topic for the study of coordination and control of networks [20]. At each time step k , agent i establishes a_i connections with neighbors denoted by $\{i_1(k), \dots, i_{a_i}(k)\}$. These interactions contribute an average appraisal of the group orientation for agent i , given by

$$U_i(k) = \frac{1}{a_i} \sum_{p=1}^{a_i} v_{ip(k)}(k). \quad (2)$$

This vector is used as input to update the orientation of agent i according to the following stochastic dynamics:

$$\theta_i(k+1) = \text{Angle}\{U_i(k)\} + \eta\zeta_i(k), \quad (3)$$

where the constant $\eta \in [0, 1]$ is the noise intensity and $\zeta_i(k)$ is a sequence of independent and identically distributed (i.i.d.) random variables drawn from a uniform distribution in $[-\pi, \pi]$.

III. PRELIMINARIES

A. Linearization of the VNM

We begin our analysis by linearizing Eq. (3) with respect to the orientation around a synchronous state, θ_0 , where $\theta_i(k) = \theta_0 + x_i(k)$. We obtain

$$x(k+1) = W(k)x(k) + \eta\zeta(k), \quad (4)$$

where $x(k) = [x_1(k) \ \dots \ x_n(k)]^\top \in \mathbb{R}^N$ is the state vector, $\zeta(k) = [\zeta_1(k) \ \dots \ \zeta_n(k)]^\top \in \mathbb{R}^N$ is the additive noise, and

Thus, we find

$$\mathbb{E}[W \otimes W] = \frac{1}{N} \text{vec}(\text{diag}(\mathbf{1} \otimes \mathbf{a})) \text{vec}(R)^\top + \frac{1}{N^2} \mathbf{1}\mathbf{1}^\top \otimes \mathbf{1}\mathbf{1}^\top.$$

Finally, the premultiplication by $R \otimes R$ yields Eq. (13). \square

A. Convergence rate in the absence of noise

The nontrivial structure of matrix G for the heterogeneous VNM in Eq. (13) hinders the direct computation of its spectral radius. To overcome this issue, we pursue a perturbation argument with respect to σ . Using the expression $a_i = K + \sigma h_i$, we write the matrix G in Eq. (13) as

$$G = G_0 + \sigma G_1 + \sigma^2 G_2 + O(\sigma^3) \quad (14)$$

where

$$G_0 = \frac{1}{KN} \text{vec}(R) \text{vec}(R)^\top, \quad (15a)$$

$$G_1 = -\frac{1}{K^2 N} \text{vec}(R \text{diag}(\mathbf{h}) R) \text{vec}(R)^\top, \text{ and} \quad (15b)$$

$$G_2 = \frac{1}{K^3 N} \text{vec}(R \text{diag}(\mathbf{h}^2) R) \text{vec}(R)^\top, \quad (15c)$$

where \mathbf{h}^2 is meant entry-wise. For $\sigma = 0$, the VNM reduces to the homogeneous scenario with $G = G_0$ studied in [17], in which all agents establish K interactions at each time-step. The simple structure of G_0 (which is a symmetric rank-1 matrix) allows to fully determine its spectrum, as summarized in the following.

Lemma 1. *The spectral radius of G_0 is $\rho_0 = \frac{N-1}{KN}$, with associated unit-length eigenvector $u_0 = \frac{1}{\sqrt{N-1}} \text{vec}(R)$. All the other eigenvalues are zero, that is, $\lambda_2 = \dots = \lambda_{N^2} = 0$.*

This implies that the rate of convergence in the homogeneous VNMs improves monotonically as the number of interactions K grows. To elucidate the effect of heterogeneity, we recall a classical result on second-order perturbation theory of simple eigenvalues, which is used to derive our second-order approximation of the spectral radius $\rho(G)$.

Proposition 2 ([34], Chapter 6). *Given a matrix G in the form Eq. (14), if the spectral radius $\rho_0 = \rho(G_0)$ is a simple eigenvalue of G_0 , then the spectral radius of G can be expressed as*

$$\rho(G) = \rho_0 + \sigma \rho_1 + \sigma^2 \rho_2 + O(\sigma^3). \quad (16)$$

The perturbation terms are equal to

$$\rho_1 = u_0^\top G_1 u_0 \quad \text{and} \quad \rho_2 = u_0^\top G_1 u_1 + u_0^\top G_2 u_0, \quad (17)$$

with $u_0 = \frac{1}{\sqrt{N-1}} \text{vec}(R)$ and

$$u_1 = \sum_{i=2}^{N^2} \frac{v_i^\top G_1 u_0}{\rho_0 - \lambda_i} v_i, \quad (18)$$

where $\lambda_2, \dots, \lambda_{N^2}$ are the $N^2 - 1$ eigenvalues of matrix G_0 different from ρ_0 , and v_2, \dots, v_{N^2} are their corresponding unit-norm eigenvectors.

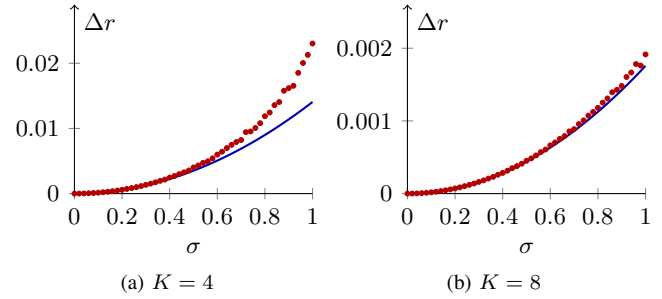


Figure 1: Variation of the spectral radius of G with respect to the one for the homogeneous VNM, $\Delta r = \rho(G) - \rho_0$, for different levels of heterogeneity σ . The blue solid curves are the analytical predictions, computed according to the second-order perturbation in Eq. (17); the red circles are Monte Carlo numerical estimation of the spectral radius of Eq. (8) over 100 independent realizations of the vector \mathbf{h} , generated randomly such that $\mathbf{1}^\top \mathbf{h} = 0$ and $\|\mathbf{h}\| = \sqrt{N}$. In both panels $N = 10$; in (a) $K = 4$, in (b) $K = 8$.

Theorem 1. *The spectral radius of the matrix G in Eq. (13) of a VNM with interaction vector \mathbf{a} is equal to*

$$\rho(G) = \frac{N-1}{KN} + \sigma^2 \frac{N-1}{K^3 N} + O(\sigma^3). \quad (19)$$

Proof. We observe that the following equalities hold: i) $\text{vec}(R)^\top G_1 = \mathbf{0}$, and ii) $\text{vec}(R)^\top \text{vec}(R \text{diag}(\mathbf{h}^2) R) = N - 1$. From i), we conclude that the first-order perturbation $\rho_1 = u_0^\top G_1 u_0 = 0$, and the first summand of ρ_2 in Eq. (17) $u_0^\top G_1 u_1 = 0$. Using ii), we compute the second summand in the expression of ρ_2 in Eq. (17), which yields the claim. \square

Remark 1. *For $\sigma = 0$, the expression in Eq. (19) reduces to $\rho(G) = \frac{N-1}{KN}$, as observed in [17]. In the presence of heterogeneity, the asymptotic convergence factor increases, hindering mean-square convergence. Specifically, we find that the increase in the spectral radius of G caused by heterogeneity is proportional to the square of the standard deviation of the interaction vector σ , while it decreases as the average number of interactions increases, being inversely proportional to the cube of K .*

The comparison between our analytical approximation and numerical computations of the spectral radius is illustrated in Fig. 1. Our numerical results support the theoretical findings in Theorem 1, suggesting that the second-order approximation derived in Eq. (19) provides an accurate estimate of the spectral radius of the matrix G up to moderate levels of heterogeneity σ . The accuracy of the approximation seems to increase with the average number of interactions K .

B. Coordination in the presence of noise

Here, we put forward a similar perturbation argument on the matrix G to derive a second-order approximation of the mean-square deviation δ_∞ in Eq. (10), which allows to approximate the polarization as in Eq. (12). The results of our analysis are summarized in the following theorem.

Theorem 2. *The mean-square deviation δ_∞ in Eq. (10) of the heterogeneous VNM with interaction vector \mathbf{a} in Eq. (12) is equal to*

$$\begin{aligned} \delta_\infty = & \eta^2 \frac{\pi^2}{3} \frac{KN(N-1)}{N(K-1)+1} \\ & + \sigma^2 \eta^2 \frac{\pi^2}{3} \frac{N(N-1)^2}{K(N(K-1)+1)^2} + O(\sigma^3). \end{aligned} \quad (20)$$

Proof. We write the term $(I \otimes I - G)^{-1}$ in Eq. (10) as a power series and we expand G using Eq. (14), obtaining

$$\begin{aligned} (I \otimes I - G)^{-1} &= I \otimes I + \sum_{n=1}^{\infty} G^n \\ &= I \otimes I + \sum_{n=1}^{\infty} G_0^n + \sigma \sum_{n=1}^{\infty} \sum_{\ell=0}^{n-1} G_0^\ell G_1 G_0^{n-\ell-1} \\ &+ \sigma^2 \sum_{n=1}^{\infty} \sum_{\ell=0}^{n-1} G_0^\ell G_2 G_0^{n-\ell-1} \\ &+ \sigma^2 \sum_{n=2}^{\infty} \sum_{\ell=0}^{n-2} \sum_{m=0}^{n-\ell-2} G_0^\ell G_1 G_0^m G_1 G_0^{n-\ell-m-2} + O(\sigma^3). \end{aligned} \quad (21)$$

From the expressions of G_0 , G_1 , and G_2 in Eq. (15), we observe that $G_0 G_1 = G_1 G_0 = G_1^2 = \mathbf{00}^\top$. Hence, the third and the fifth terms in Eq. (21) are equal to 0. We substitute the remaining terms of Eq. (21) into Eq. (10), obtaining three contributions to the expression of δ_∞ , up to the $O(\sigma^3)$ term. Specifically, we have two zeroth-order terms and one second-order term in σ , coming from the first, second, and fourth summands in Eq. (21), respectively. The first two terms yield the mean-square deviations for an homogeneous VNM with K interactions, which is equal to $\eta^2 \frac{\pi^2}{3} \frac{KN(N-1)}{N(K-1)+1}$, as computed in [17]. Finally, we compute

$$\begin{aligned} & \eta^2 \frac{\pi^2}{3} \text{vec}(R)^\top \left(\sigma^2 \sum_{n=1}^{\infty} \sum_{\ell=0}^{n-1} G_0^\ell G_2 G_0^{n-\ell-1} \right) \text{vec}(R) \\ &= \eta^2 \frac{\pi^2}{3} \sigma^2 \sum_{n=1}^{\infty} \sum_{\ell=0}^{n-1} \left(\frac{N-1}{NK} \right)^{n-1} \text{vec}(R)^\top G_2 \text{vec}(R) \\ &= \eta^2 \frac{\pi^2}{3} \sigma^2 \sum_{n=1}^{\infty} n \left(\frac{N-1}{NK} \right)^{n-1} \frac{(N-1)^2}{NK^3} \\ &= \eta^2 \frac{\pi^2}{3} \frac{(N-1)^2}{NK^3} \sigma^2 \frac{1}{\left(1 - \frac{N-1}{NK}\right)^2} \\ &= \eta^2 \frac{\pi^2}{3} \sigma^2 \frac{N(N-1)^2}{K(N(K-1)+1)^2}. \end{aligned}$$

□

Remark 2. *From Eq. (20), one can compute an approximation of the polarization in Eq. (12) that is valid for small added noise. For $\sigma = 0$, this expression reduces to the one computed by [17] for the homogeneous VNM; for $\sigma > 0$, the polarization decreases, such that the presence of heterogeneity hinders coordination.*

We compare the closed-form expression for the polarization based on Eq. (12) and Eq. (20), with Monte Carlo estimations of Eq. (11), computed by numerically simulating the nonlinear

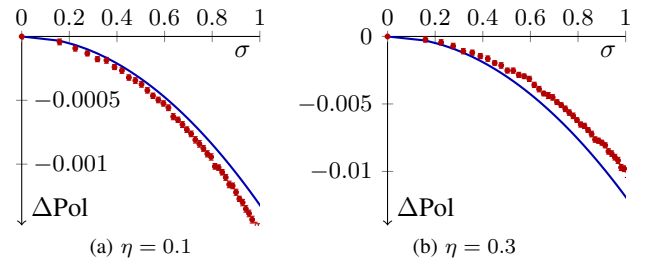


Figure 2: Variation of the polarization with respect to the homogeneous VNM, $\Delta\text{Pol} = \text{Pol} - \text{Pol}_0$, where Pol_0 is the polarization of the homogeneous VNM, for different levels of heterogeneity σ . The blue solid curves are the analytical predictions of Pol based on Eq. (12) and Eq. (20), the red circles are Monte Carlo estimations of Pol from Eq. (11) over 100 independent runs of the nonlinear VNM. Parameters are $N = 80$, $K = 3$, with (a) $\eta = 0.1$ and (b) $\eta = 0.3$. The interaction vectors \mathbf{a} are constructed for given values of σ such that $\mathbf{1}^\top \mathbf{h} = 0$, $\|\mathbf{h}\| = \sqrt{N}$.

VNM. Simulations are conducted for $N = 80$ agents, initialized at $\theta_i(0) = 0$, for $i = 1, \dots, N$. For each simulation, the model is run for 5,000 time-steps and the polarization is computed by averaging the quantity in Eq. (11) over the last 4,000 steps.

In Fig. 2, we investigate the effect of heterogeneity on the polarization by comparing the difference with respect to the heterogeneous VNM. Besides confirming our intuition that heterogeneity hampers coordination, our results suggest that the second-order approximation is accurate for moderate levels of heterogeneity, that is, up to $\sigma \approx 0.5$.

In Fig. 3, we compare the numerical estimation of the polarization from the simulations and the closed-form approximation, for different levels of the heterogeneity σ , noise η , and average number of interactions K . Our results suggest that the closed-form solution is able to accurately capture the coordination of the heterogeneous VNM up to moderate values of $\eta \approx 0.5$, after which the nonlinear model reaches the completely-discordant state that cannot be predicted by a linear model. The heterogeneity has a secondary role on the extent of the coordination, due to the fact that dependence of the mean-square deviation Eq. (20) with σ^2 is moderated by $K(K-1)^2$ for $N \gg 1$.

V. CONCLUSIONS

In this work, we investigated the effect of heterogeneity on the vectorial network model, a stochastic protocol that is used to examine collective motion of groups of agents. By linearizing the dynamics about a synchronous state and leveraging techniques from stochastic consensus and eigenvalue perturbation theories, we established closed-form results for the asymptotic behavior of the model. First, we computed a second-order approximation for the asymptotic convergence factor, which governs the mean-square convergence of the model in the absence of noise. Second, we derived an expression for the polarization of the system, which measures the level of coordination between the agents.

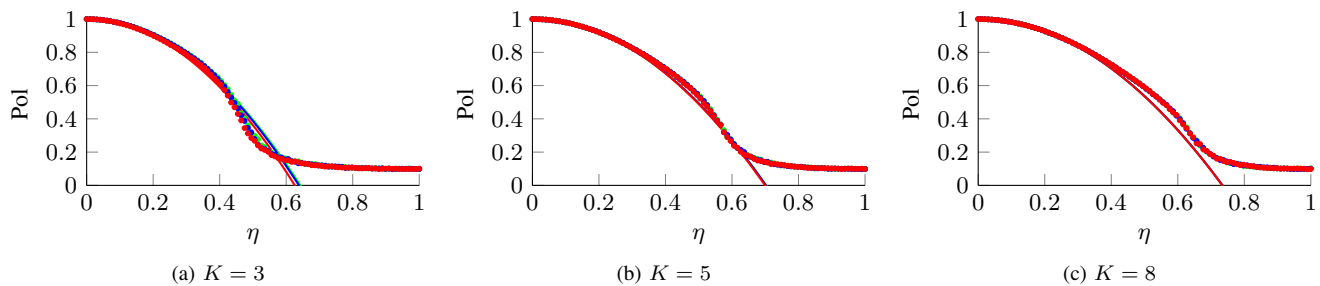


Figure 3: Polarization for different values of noise η . We consider $N = 80$ agents with three different levels of heterogeneity: $\sigma = 0$ (green), $\sigma = 0.5$ (blue), and $\sigma = 1$ (red) and three different average number of interactions (a) $K = 3$, (b) $K = 5$, and (c) $K = 8$. The solid curves are analytical predictions and circles are Monte Carlo estimations over 100 independent runs of the nonlinear VNM. The interaction vectors \mathbf{a} are constructed for given values of σ such that $\mathbf{1}^\top \mathbf{h} = 0$, $\|\mathbf{h}\| = \sqrt{N}$.

Our results support the intuition that heterogeneity has a detrimental effect on coordination, whereby both the convergence rate and the polarization are reduced as heterogeneity increases. However, the extent of this effect is nonlinearly moderated by the average number of connections made by the agents. From a biological point of view, the robustness of the system to heterogeneity might be a gateway for the emergence of differences in the individual traits of the group that have been shown to beget advantages to life in groups [24]. In linking the predictions of the vectorial network model to more complex models of collective motion, future efforts should explore the role of state-dependent stochastic dynamics.

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