Early Warning Signals and Sentinel Nodes in Network Epidemics

Keywords: epidemic networks, early warning signals, Ornstein–Uhlenbeck process, spectral analysis, sentinel nodes

Extended Abstract

Motivation. Understanding and predicting epidemic outbreaks on networks is a central problem in complex systems. Classical epidemic models show that the outbreak threshold depends on network structure, particularly the largest eigenvalue of the adjacency matrix. More recently, early warning signals (EWS), such as variance growth near critical transitions, have been proposed as tools for anticipating system-wide changes. We begin by recognizing a limitation of existing network-based early warning systems. Traditional centrality-based monitoring—such as observing nodes with high degree or betweenness—has proven effective in identifying influential spreaders and flattening infection peaks by targeted testing or isolation. As shown by [5] and [4], monitoring high-centrality nodes in real contact networks can drastically delay and lower epidemic peaks. However, as [1] emphasize in the context of regime-shift anticipation, no single node or signal is universally optimal: correlations between nodes, heterogeneous noise, and multistage transitions limit the performance of node-level early warning strategies. However, an important gap remains: nodes that provide strong early warning signals are not necessarily those that most effectively control disease spread. This study addresses two key questions: how network structure shapes early warning signals near the epidemic threshold, and whether nodes identified via EWS are effective targets for intervention.

Approach and Methodology. We consider a network-based SIR model, which we extend the SIR in [2], on a fixed contact network with $N = 148$ nodes. Linearizing the dynamics near the disease-free equilibrium yields a system governed by $\beta A - \gamma I$, leading to the epidemic threshold $\beta_c = \gamma / \lambda_{\max}(A)$. Near this threshold, the system is approximated by a multivariate Ornstein–Uhlenbeck process [3].

We quantify fluctuations using both stochastic simulation (Euler–Maruyama) and analytical covariance derived from spectral decomposition. Node-level variances are computed for a range of transmission rates below β_c. To identify informative nodes, we adopt a signal-to-noise separation metric (d-metric) following [1], comparing variance changes between two precritical regimes. Nodes are ranked by this metric, and the top 10% are defined as sentinel nodes. These are compared against nodes selected by betweenness centrality (BC).

Results. As β approaches β_c, node-level variances increase, consistent with critical slowing down. However, this increase is heterogeneous across the network. Nodes aligned with the leading eigenvector exhibit rapid variance growth but also large fluctuations, reducing detectability. In contrast, sentinel nodes identified by the d-metric show more consistent and lower-noise variance increases.

A clear distinction emerges between detection and control. Removing high-BC nodes significantly suppresses epidemic spread, reducing peak infection levels. In contrast, removing high-EWS nodes has minimal impact on epidemic dynamics (Fig.1). This demonstrates that nodes optimal for early detection are not optimal for intervention.

Conclusions and Outlook. Early warning signals in network epidemics are strongly shaped by spectral structure and noise. Sentinel nodes provide reliable detection of critical transitions but are not effective control targets. This highlights a fundamental separation between monitoring and intervention strategies. Future work will extend this framework to temporal and weighted networks, and explore hybrid strategies combining structural and statistical indicators.

References

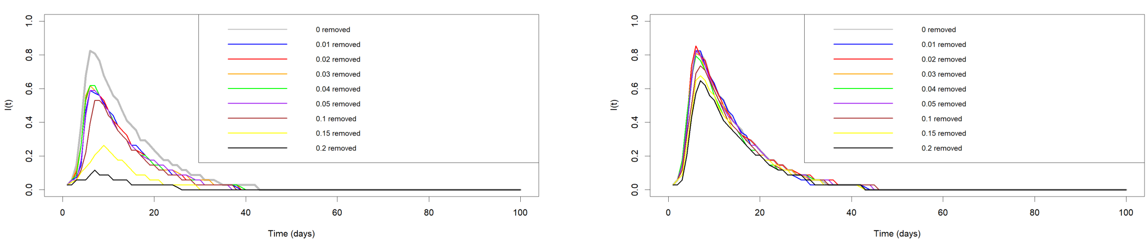
[1] Naoki Masuda, Kazuyuki Aihara, and Neil G. MacLaren. Anticipating regime shifts by mixing early warning signals from different nodes. *Nature Communications*, 15, 12 2024.

[2] Romualdo Pastor-Satorras, Claudio Castellano, Piet Van Mieghem, and Alessandro Vespignani. Epidemic processes in complex networks. *Rev. Mod. Phys.*, 87:925–979, Aug 2015.

[3] Amy Chian Patterson, Alexander G. Strang, and Karen C. Abbott. When and where we can expect to see early warning signals in multispecies systems approaching tipping points: Insights from theory. *The American Naturalist*, 198(1):E12–E26, 2021. PMID: 34143719.

[4] Fatimah Abdul Razak and Paul Expert. Modelling the spread of covid-19 on malaysian contact networks for practical reopening strategies in an institutional setting. *Sains Malaysiana*, 50:1497–1509, 5 2021.

[5] Fatimah Abdul Razak and Zamira Hasanah Zamzuri. Modelling heterogeneity and super spreaders of the covid-19 spread through malaysian networks. *Symmetry*, 13, 10 2021.



(a) High betweenness centrality monitoring

(b) High early warning signal monitoring

Figure 1: **Comparison of intervention strategies.** Removing high-BC nodes suppresses the epidemic, while removing high-EWS nodes has limited effect.