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Focus on the disruption of networks and system dynamics

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ABSTRACT

Networks are designed to ensure proper functioning and sustained operability of the underlying systems. However, disruptions are generally unavoidable. Internal interactions and external environmental effects can lead to the removal of nodes or edges, resulting in unexpected collective behavior. For instance, a single failing node or removed edge may trigger a cascading failure in an electric power grid. This Focus Issue delves into recent advances in understanding the impacts of disruptions on networks and their system dynamics. The central theme is the disruption of networks and their dynamics from the perspectives of both data-driven analysis as well as modeling. Topics covered include disruptions in the dynamics of empirical systems such as nuclear reaction networks, infrastructure networks, social networks, epidemics, brain dynamics, and physiology. Emphasis is placed on various phenomena in collective behavior, including critical phase transitions, irregular collective dynamics, complex patterns of synchrony and asynchrony, chimera states, and anomalous oscillations. The tools used for these studies include control theory, diffusion processes, stochastic processes, and network theory. This collection offers an exciting addition to the evolving landscape of network disruption research.

I. INTRODUCTION

Networks possess both structural and functional properties that are far from being fully understood. The interactions between adjacent units and their coupling to other parts crucially determine the system's response to external influences. Disruption can have dual effects; it may not always induce undesirable outcomes but can also limit signal propagation between regions, thereby acting as a form of information control.[1] Most real-world systems operate in open environments, exchanging material, energy, or information with their surroundings.[2] This constant exchange subjects systems to disturbances of varying intensities and types, some of which can disrupt networks by removing components (nodes or edges). System dynamics can amplify local effects, potentially extending them throughout the entire system and causing catastrophic failures.[3]

A representative example is the cascading failure in an electric power grid:[4–6] When components of the power grid (generator sets or transmission lines) fail and disconnect due to natural or human factors, the system redistributes its load. This redistribution can overload other transmission lines, causing them to disconnect due to protective measures or overheating. If this chain reaction continues, it can lead to large-scale power outages, resulting in significant economic and social losses. Other examples include disruptions in supply networks,[7] infrastructure networks,[8,9] neural networks,[10,11] and neurodegenerative diseases.[12]

Whether a system can maintain normal operations after a disruption depends on the both network structure and system dynamics and, ultimately, the interplay between them. This interplay can turn relatively minor disruptions into extensive destruction.[13] Consequently, much research has focused on understanding the relationship between disruption effects, network structure, and system dynamics. This research can be broadly divided into two directions. To avoid disruptions in the first place, it is essential to enhance the resilience of systems to minimize the possibility of extensive destruction.[14,15] Common approaches include adjusting the network structures and dynamical parameters[16–18] based on theoretical analysis, as well as detecting and reinforcing critical or vulnerable components[19–22] whose failures could be catastrophic for the system. After a disruption, it is crucial to suppress cascading effects,[23] repair damaged parts,[24,25] and promptly restore the system's major functions[26,27] to prevent further damage. In summary, the ultimate goal of studies in this field is to minimize the impact of disruptions on the normal operation of systems, based on a thorough understanding of the interplay between the network structure and system dynamics.

This Focus Issue is dedicated to recent advances in understanding the effects of disruptions on networks and their system dynamics. It aims to promote research into how the network structure and dynamics together determine system behavior in response to various disruptive attacks. Below, we provide a concise summary of each article in this Focus Issue. These papers explore disruptions in both empirical systems' dynamics (e.g., nuclear reaction networks, infrastructure networks, social networks, epidemics, brain dynamics, and physiology) and various phenomena of collective behaviors (e.g., critical phase transitions, irregular collective dynamics, complex patterns of synchrony and asynchrony, chimera states, and anomalous oscillations). Methods employed include control theory, stochastic processes, network theory, and other exciting tools. The 24 papers in this Focus Issue are broadly divided into four categories, strategically exploring the interplay between network structure and dynamics when facing disruptive attacks.

A. Resilience

The scale of destruction to networks and their dynamics after a disruption largely depends on the system's ability to withstand disturbances—its resilience. How resilience is influenced by the underlying network topology and various dynamical parameters is not fully understood, yet it is imperative for understanding, control, and mitigation strategies. The key factors contributing to resilience are investigated in the following papers:

The study titled "*A Combat Game Model with Inter-Network Confrontation and Intra-Network Cooperation*" by Chen *et al.*[28] investigates the influence of the structure and cooperation on winning percentages. They proposed a two-network combat game model and designed corresponding rules for attacking and cooperating within four common network structures. Their results show that the network structure plays a crucial role in the combat outcomes of two structured systems. Their model could deepen our understanding of the effects of the structure and cooperation in combat scenarios and can be applied to various combat games.

The research article titled "*An Improved Approach for Calculating the Energy Landscape of Gene Networks from Moment Equations*" by Bian *et al.*[29] proposes an Extended Gaussian Approximation (EGA) approach that considers the effects of third moments. Compared to the Weighted Summation from Gaussian Approximation (WSGA), EGA provides a more accurate method for calculating and quantifying the landscape of multistable dynamical systems.

The publication entitled "*Bifurcations in Adaptive Vascular Networks: Toward Model Calibration*" by Klemm and Martens[30] studies a mathematical model of vascular network adaptation, where the network structure dynamically adjusts to changes in blood flow and pressure. By comparing model predictions with experimental data, they calibrated the cost exponent to align the model with the data and highlighted some limitations of the model.

The article named "*Collective Excitability in Highly Diluted Random Networks of Oscillators*" by Paolini *et al.*[31] reports on collective excitable events in a highly diluted random network of non-excitable nodes. By gradually decreasing the percentage of coupled nodes, they demonstrate the remarkable robustness of collective excitability against network diluteness, which is related to hidden geometric structures that organize the mean field trajectories in the phase space.

The paper named "*Extreme Rotational Events in a Forced-Damped Nonlinear Pendulum*" by Pal *et al.*[32] explores intermittent extreme rotational events detected in the rotational dynamics of a two-dimensional forced-damped pendulum under the influence of AC and DC torque. They identify a sudden increase in the size of the chaotic attractor due to an interior crisis as the source of instability triggering large amplitude events.

The work titled "*Synchronization Stability of Power-Grid-Tied Converters*" by Ma *et al.*[33] studies synchronization stability in renewable-dominated power systems based on different nonlinear models. They clarified the key role of the phase-locked loop (PLL) in synchronization stability and revealed that the synchronization stability of converters is rooted in the phase synchronization concept in nonlinear science.

B. Impact of disturbances

There are many ways a system can be disturbed. Extensive studies on specific disturbance forms applied to systems enhance our understanding of nonlinear dynamics mechanisms and provide guidance for targeted measures. The following papers significantly contribute to this theme:

The study titled "*Cluster Synchronization Induced by Manifold Deformation*" by Wang *et al.*[34] studies the pinning control in a globally connected network of chaotic oscillators. When the pinning strength exceeds a critical value, the oscillators synchronize into two different clusters: one formed by the pinned oscillators and the other by the unpinned oscillators. By examining the trajectories in the phase space, it was found that the deformed synchronization manifold causes the failure to predict the behaviors of unpinned oscillators.

The research article titled "*Direction-Dependent Noise-Induced Synchronization in Mobile Oscillators*" by Shajan *et al.*[35] proposes a direction-dependent noise field model for noise-induced synchronization of an ensemble of mobile oscillators/agents, where the effective noise on each moving agent is a function of its direction of motion. They observed not only complete synchronization of all the oscillators but also clustered states as a function of ensemble density beyond a critical value of noise intensity.

The publication entitled "*Faster Network Disruption from Layered Oscillatory Dynamics*" by Tyloo[36] investigates the influence of noise with system-specific correlations on the first escape time of nonlinearly coupled oscillators embedded in layered complex networks. The paper shows that strong amplification of fluctuations and the spatial and temporal correlations of noise along the lowest-lying eigenmodes of the Laplacian matrix are threats to the network's functionality.

The article named "*Heterogeneity Induced Splay State of Amplitude Envelope in Globally Coupled Oscillators*" by Liu *et al.*[37] introduces heterogeneous nodes into globally coupled identical oscillators with repulsive coupling and observed splay states of the amplitude envelope. Increasing the frequency mismatches between the heterogeneous nodes made the formerly stable splay state unstable, while a new splay state based on the new-born amplitude envelopes was stably observed among the remaining identical oscillators.

The paper named "*Investigation on the Influence of Heterogeneous Synergy in Contagion Processes on Complex Networks*" by Yan *et al.*[38] introduces individual-based heterogeneity with a power-law form into the synergistic susceptible–infected–susceptible model and investigated the synergistic contagion process on complex networks. The paper analytically demonstrated that heterogeneous synergy significantly changes the critical threshold of synergistic strength required for discontinuous phase transitions in contagion processes.

The work titled "*Phase Frustration Induced Remote Synchronization*" by Yang *et al.*[39] introduces phase frustration into an oscillator system and found that remote synchronization can be induced in systems where no remote synchronization exists without phase frustration. The optimal range was shown to be related to the match of phase frustrations between the hub and leaf nodes.

C. Identifying critical system components

Identifying the critical components of a system is essential for understanding its resilience to disturbances. Components vary in their importance with respect to disruptions. The failure of critical components can cause massive destruction in a short time, whereas the failure of less important ones may only cause limited damage. The following papers identify and study critical components, thereby highlighting which parts of the system should be closely monitored and safeguarded.

The study titled "*A Perturbation-Based Approach to Identifying Potentially Superfluous Network Constituents*" by Bröhl and Lehnertz[40] derived a perturbation-based method to identify potentially superfluous network constituents in the construction of networks from empirical time-series data. This method utilizes vertex and edge centrality concepts, whose effectiveness is verified through common network structures.

The research article titled "*Delta-Alpha Cross-Frequency Coupling for Different Brain Regions*" by Lukarski *et al.*[41] applied an adaptive dynamic Bayesian inference method to electroencephalogram (EEG) measurements of healthy resting subjects to reconstruct neural cross-frequency coupling functions between different brain regions. The results showed that in certain regions, the influence of delta oscillations on alpha oscillations is more pronounced and that oscillations influencing others are more evenly distributed across brain regions than those being influenced.

The publication entitled "*Impact of Random and Targeted Disruptions on Information Diffusion During Outbreaks*" by Masoomy *et al.*[42] studied a multiplex epidemic model consisting of an information layer and a spatially embedded epidemic layer. By calibrating the model to the early outbreak stages of the SARS-CoV-2 pandemic in 2020, the paper illustrated that targeted disruptions of hub nodes that exchange information with many individuals can abruptly change outbreak characteristics. This emphasizes the importance of maintaining robust communication infrastructure during an outbreak.

The article named "*Non-Negative Matrix Factorization for Overlapping Community Detection in Directed Weighted Networks with Sparse Constraints*" by Wang *et al.*[43] proposed a novel attribute-information non-negative matrix factorization approach. This method integrates sparse constraints and optimizes an objective function for detecting communities in directed weighted networks, uncovering the intricate iterative process of system evolution toward convergence.

The paper named "*Ranking Cliques in Higher-Order Complex Networks*" by Zhao *et al.*[44] proposed several higher-order centralities to quantify and rank the importance of cliques. Experiments on both synthetic and real-world networks demonstrate that, compared with traditional network metrics, the proposed higher-order centralities effectively reduce the dimensionality of large-scale networks and are more accurate in identifying a set of vital nodes.

The work titled "*Scenarios for a Post-COVID-19 World Airline Network*" by Ye *et al.*[45] introduced the airline company network to study the influence of airline company bankruptcies on the connectivity of the world airline network. By analyzing traffic data during the early stage of the COVID-19 outbreak, the paper revealed the serious consequences induced by the bankruptcies of airline companies with significant monopolistic characteristics.

D. Prevention and restoration

Because attacks cannot always be prevented, it is crucial to consider how to minimize the damage to the system once they occur. This can be achieved through two approaches: prevention and restoration. Despite their distinct tasks, these approaches are not mutually exclusive and offer diverse solutions. The following papers offer critical insights into these strategies.

The study titled "*An Optimization-Based Algorithm for Obtaining an Optimal Synchronizable Network After Link Addition or Reduction*" by Parastesh *et al.*[46] proposed an optimization algorithm based on the eigenvalues of the connectivity matrix to construct a network with optimal synchronization. This algorithm can also be applied to reduce links while minimally disturbing the network's synchronization.

The research article titled "*Designing Spiking Neural Networks for Robust and Reconfigurable Computation*" by Börner *et al.*[47] presented an analytical approach to derive parameters that allow a network of spiking neurons to be robustly reconfigured after the removal of a neuron and its connections. The paper provided an effective method for designing spiking neural network computing systems with disruption-resilient dynamics.

The publication entitled "*Multivariate Recovery Coupling in Interdependent Networks with Cascading Failure*" by Li *et al.*[48] developed a multivariate recovery coupling model for interdependent networks based on percolation theory. It was found that the supporting network plays a more crucial role in improving network resilience than the network where the repaired component is located, as a recovery strategy based on local stability is more likely to yield direct benefits.

The article named "*Percolation Transitions in Interdependent Networks with Reinforced Dependency Links*" also by Li *et al.*[49] introduced a percolation model for studying interdependent networks by reinforcing a fraction of dependency links. The paper identified a minimum fraction of dependency links that need reinforcement to prevent abrupt network transitions and demonstrated that this method has higher reinforcement efficiency compared to node-reinforcement strategies.

The paper named "*Promoting Synchrony of Power Grids by Restructuring Network Topologies*" by Li *et al.*[50] extensively studied the optimization of power grid topology through connection rewirings and proposed the frequency-correlation-optimization scheme. The optimized topology features more generator–consumer connections, indicating that decentralizing the distribution of generator nodes on power grids enhances synchronizability.

The work titled "*Recursive Traffic Percolation on Urban Transportation Systems*" by Chen *et al.*[51] proposed a recursive traffic percolation framework to capture the dynamics of cascading failures and analyze potential overloaded bottlenecks, considering the influence of external flow. By improving the capacity of identified bottlenecks, the global flow benefits and the phase transition of percolation are delayed.

II. CONCLUSION

Past and current research has only begun to unveil the intricate interplay between the network structure and dynamics. This Focus Issue demonstrates the richness of questions and problems that arise when networked dynamical systems are disrupted. The collection of papers summarized here explores this topic in great depth. Despite the significant progress made, the diversity of disruptions and the unpredictability of complex systems make fully understanding the relationship between the effects of disruption, network structure, and system dynamics a challenging goal. However, we believe these works provide a solid foundation for future research in this area.

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