DYNAMIC SIMULATION AND POLICY OPTIMIZATION OF EPIDEMIC SPREAD IN HETEROGENEOUS NETWORKS

A Study Based on the Susceptible-Infectious-Recovered-Susceptible Model

by

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This study investigates the dynamic processes of epidemic spread and policy optimization in heterogeneous Barabasi-Albert networks using the susceptible-infectious-recovered-susceptible model. By systematically adjusting key parameters, including the number of inter-subnetwork connections, the number of subnetworks, and node connection strategies, we conducted a comprehensive analysis of the impact of these factors on epidemic transmission. This analysis revealed the critical role of network structure in disease spread. The findings indicate that augmenting inter-subnetwork connections and node connections expedites the propagation of the epidemic, culminating in elevated infection peaks but diminished overall epidemic durations. The model validation is further substantiated by the use of real-world data from the outbreak of the novel coronavirus disease in Wuhan, China, with the simulation results demonstrating a close alignment with the observed trends. This finding serves to substantiate the model's efficacy. Studies on policy optimization have indicated that the premature relaxation of control measures can result in elevated infection peaks. Conversely, the easing of measures at opportune times can facilitate more effective epidemic control. This research establishes a theoretical framework for public health decision-making, particularly in terms of balancing epidemic control with socio-economic recovery.

Keywords: *epidemic spread, heterogeneous Barabasi-Albert networks, susceptible-infectious-recovered-susceptible model, simulation analysis, policy optimization*

Introduction

The propagation of infectious diseases is a multifaceted process influenced by various factors, including population connectivity, network structure, and individual behavior. It is imperative to comprehend these dynamics to formulate efficacious public health interventions, especially in the context of large-scale epidemics such as the ongoing outbreak of severe acute respiratory syndrome (SARS-CoV-2). In recent years, network-based models have gained prominence for their ability to capture the heterogeneous nature of human interactions, which play a critical role in disease transmission [1-3]. Among these, the Barabasi-Albert (BA) scale-free network model has been extensively employed to study epidemic spread due

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to its capacity to represent real-world networks with highly connected *super-spreader* nodes [4-6]. However, the majority of extant studies have focused on homogeneous networks, thereby creating a lacuna in the understanding of how epidemic dynamics unfold in heterogeneous networks with multiple interconnected subnetworks.

This study builds on previous work on BA networks and the susceptible-infectious-recovered-susceptible (SIRS) model [7, 8] to explore the simulation and optimization of epidemic spread in heterogeneous networks. The introduction of multiple subnetworks, which represent distinct urban areas or communities, is intended to provide a more fine-grained understanding of how local and global network structures influence disease transmission. Specifically, the present study investigates the effects of key network parameters, such as the number of inter-subnetwork connections, the size and number of subnetworks, and node connection strategies, on epidemic metrics like peak infection rates and overall duration.

A notable strength of this study is its incorporation of real-world data to assess the model predictive capabilities. Utilizing data from the outbreak of the novel coronavirus known SARS-CoV-2 in Wuhan, China, the model capacity to replicate observed epidemic trends is demonstrated, thereby enhancing its reliability for guiding public health policies. Furthermore, we explore the impact of policy interventions, such as the timing of *opening-up* measures, on epidemic trajectories. This analysis offers significant insights into how policymakers can judiciously balance epidemic control with socio-economic recovery.

The objectives of this study are twofold:

- *Simulation analysis:* The objective of this study is to evaluate how variations in network parameters – such as inter-subnetwork connections, subnetwork sizes, and node connection strategies – affect epidemic spread dynamics, including peak infection rates and total duration.
- The following section will address the optimization of models. The following example illustrates how modifying contact rates or implementing *opening-up* policies at varying stages of an epidemic can modify its trajectory. This, in turn, can inform more targeted and effective public health measures.

The integration of theoretical simulations with real-world validation has enabled significant advancements in our understanding of epidemic spread in heterogeneous networks. This study offers practical guidance for the design and optimization of public health interventions. Subsequent research endeavors will entail the incorporation of supplementary real-world factors, including individual behavioral modifications and diverse intervention strategies, with the objective of further enhancing the model's precision and relevance.

Simulation results analysis

In order to investigate the dynamics of epidemic spread in heterogeneous networks, a series of simulations were conducted using the SIRS model on BA networks. The simulations were designed to explore the effects of key network parameters, including the number of inter-subnetwork connections, the number of subnetworks, and the node connection strategy. The ensuing section presents the results of these simulations and analyzes their implications for epidemic transmission.

Influence of inter-subnetwork connections

The initial step in our methodology was to construct a BA network with 5000 nodes, which were divided into 10 subnetworks of varying sizes. In order to examine the impact of inter-subnetwork connectivity, the number of connections between subnetworks was varied

(2, 5, and 10) and simulations were run for 200 discrete time steps. The findings indicated that augmenting the quantity of inter-subnetwork connections resulted in a heightened and more premature infection peak. This phenomenon can be attributed to the increased connectivity between subnetworks, which establishes additional pathways for viral transmission, thereby accelerating the spread across different regions. However, the overall duration of the epidemic was found to be shorter in networks with more connections, as a larger portion of the population gained immunity more quickly. These findings underscore the trade-off between the speed of epidemic spread and its duration, a critical consideration in the design of containment strategies. The results of this study are illustrated in fig. 1.

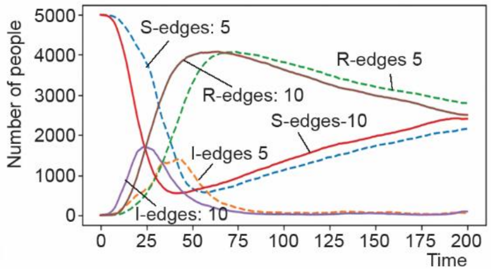

Figure 1. The SIRS model simulation results under different numbers of inter-subnetwork connections

Influence of different numbers of subnetworks

In the subsequent phase of the study, the effect of modifying the number of subnetworks while maintaining a constant total of 5000 nodes and a fixed number of five inter-subnetwork connections was examined. Two scenarios were compared: one with five subnetworks and another with 10 subnetworks. The simulation results indicated that, in most cases, the number of subnetworks had a limited impact on disease transmission under uniform random connection strategies. However, when the network was subdivided into 10 subnetworks, the infection peak was marginally higher and occurred earlier compared to the case with five subnetworks. This phenomenon can be attributed to the presence of central nodes (hubs) in BA networks. With a reduced number of subnetworks, each subnetwork contains a greater number of nodes, thereby increasing the probability of central nodes becoming infected and accelerating the spread of the disease. The results of this study are presented in fig. 2.

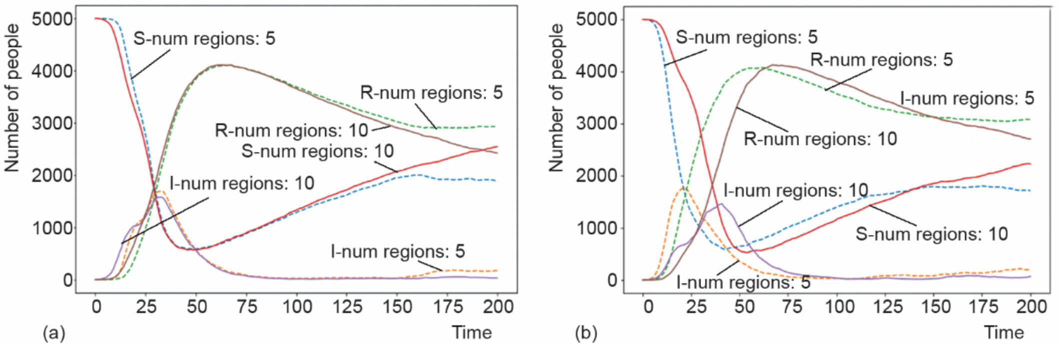

Figure 2. The SIRS model simulation results; (a) different numbers of subnetworks and (b) different numbers of subnetworks

Influence of BA network generation strategy

A final investigation was conducted to determine the impact of varying node connection strategies on the propagation of epidemics. Two scenarios were considered: one in

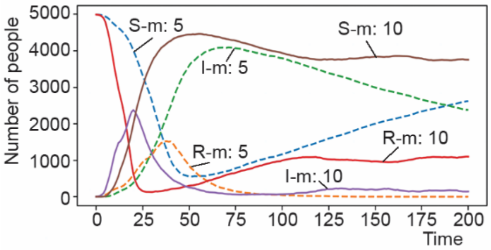

Figure 3. The SIRS model simulation results under different node connection numbers

which each new node connected with five existing nodes, and another in which each new node connected with ten existing nodes, while maintaining five inter-subnetwork connections. The simulations demonstrated that increasing the number of connections per node led to an earlier and higher infection peak. This phenomenon can be attributed to the fact that an increase in connections corresponds to a greater number of opportunities for contact between infected and susceptible individuals, thereby facilitating a more rapid transmission process. However, the epidemic duration was found to be shorter in the network with 10 connections per node compared to the network with five connections, as herd immunity was achieved more quickly in the former. These findings underscore the importance of network connectivity in shaping the trajectory of an epidemic. The results of this study are presented in fig. 3.

Model validation and optimization

In order to ensure the reliability and practical applicability of the network-based SIRS model, the researchers conducted validation using real-world data from the outbreak of the novel coronavirus known as SARS-CoV-2 in Wuhan, China. Furthermore, we investigated the impact of policy interventions, including the timing of *opening-up* measures, on epidemic trajectories. This section presents the results of model validation and policy optimization, highlighting their implications for public health decision-making.

Feasibility testing using real data

The SIRS model was validated using data from the 2020 outbreak of the novel coronavirus in Wuhan. A network comprising 13 nodes was constructed, with each node representing one of Wuhan's 13 administrative districts. The network was further configured with two links between each pair of districts, thereby simulating inter-district interactions. The model parameters, which include transmission rates, recovery times, and reinfection probabilities, were calibrated based on observed data. The simulation results demonstrated that, while the simulated infection numbers exhibited a slight increase over the actual observations, the overall trends aligned with the real-world data. This outcome demonstrates the model capacity to encapsulate the fundamental dynamics of the epidemic. Furthermore, the timing of infection peaks in the simulations closely matched the actual outbreak, providing strong support for the model validity. The results of this study are summarized in tab. 1 and illustrated in figs. 4-6.

Table 1. Records of four experimental results (bimodal cases)

	Occurrence time [days]				Peak value [persons]			
Number of trials	1	2	3	4	1	2	3	4
First peak	23	28	24	22	287	282	270	231
Second peak	51	47	53	43	469	464	356	430

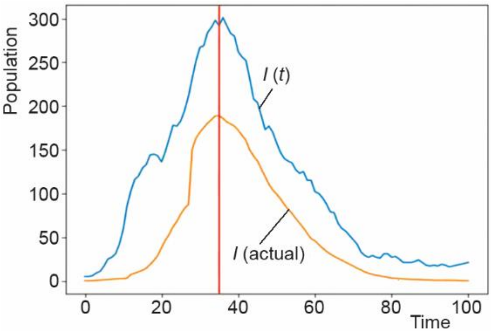

Figure 4. Comparison between actual and model-predicted case numbers

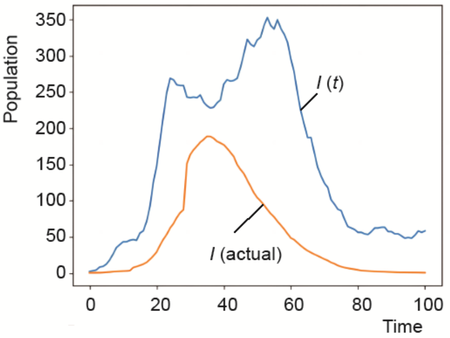

Figure 5. Comparison of infection numbers (bimodal cases)

Network model optimization

Utilizing a validated model as a foundation, this study examined the impact of various *relaxation* or *opening-up* strategies on epidemic trajectories. In the simulations, the contact rate was increased on predetermined days (*e.g.*, the 10th, 15th, 20th, or 25th day) by modifying the number of connections per node from five to ten within each subnetwork. The findings indicated that early relaxation, specifically on the 10th day, resulted in a notably higher infection peak. Conversely, the easing of measures around the 15th, 20th, or 25th day led to a lower and later peak. This suggests that delaying relaxation measures can effectively flatten the epidemic curve, reducing the burden on healthcare systems and allowing for more controlled reopening. These findings underscore the imperative of optimizing the timing of policy implementation to achieve a balance between epidemic control and socio-economic recovery. The results of this study are illustrated in fig. 7.

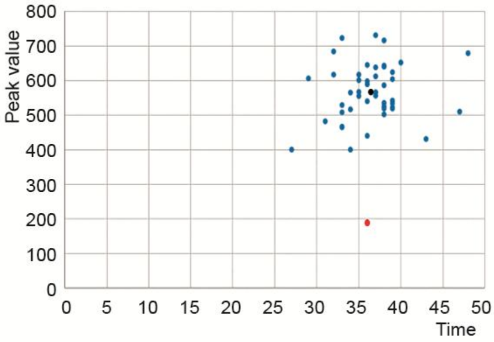

Figure 6. Results from 46 simulation experiments

Conclusions

This study has thoroughly examined the dynamics of epidemic propagation in heterogeneous BA networks through simulations and real-world data validation. By systematically varying key network parameters, such as the number of inter-subnetwork connections, the number of subnetworks, and the node connection strategy, we have demonstrated the significant influence of network structure on epidemic transmission. The simulation results indicated that augmenting inter-subnetwork connections and node connectivity expedites the propagation of the epidemic, culminating in elevated and premature infection peaks, while concomitantly reducing the overall duration. These findings underscore the critical role of network topology in shaping the trajectory of an epidemic.

The validation of the SIRS model using real-world data from the outbreak of the novel coronavirus disease in Wuhan, China, further confirmed the model ability to capture the essential dynamics of epidemic spread. The close alignment between simulated and actual in-

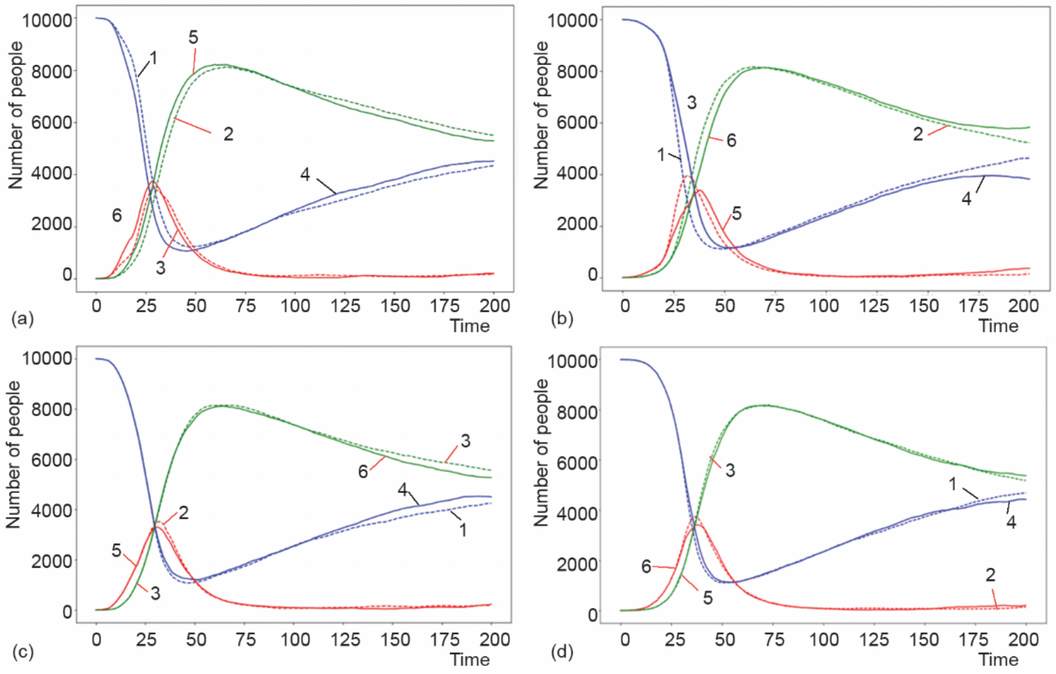

Figure 7. The SIRS simulation; (a) 10 days, (b) 15 days, (c) 20days, and (d) 25 days;
1 – susceptible – original, 2 – infected – original, 3 recovered – original, 4 – susceptible – modified, 5 – infected – modified, and 6 – recovered - modified

fection trends, particularly in the timing of infection peaks, underscores the model reliability and predictive capacity. This validation establishes a substantial foundation for the utilization of the model in informing public health decision-making.

Furthermore, studies on policy optimization have underscored the significance of temporal considerations in implementing *opening-up* measures. The initial relaxation of control measures resulted in a substantial increase in infection peaks, while delaying such measures led to a reduction in later peaks, effectively flattening the epidemic curve. These insights are of paramount importance for policymakers seeking to balance epidemic control with socio-economic recovery, particularly in the context of large-scale outbreaks like the one caused by the SARS-CoV.

This study contributes to our understanding of epidemic spread in heterogeneous networks by underscoring the role of network parameters in shaping transmission dynamics. The integration of the SIRS model with BA networks furnishes a robust framework for analyzing complex epidemic scenarios, aligning with recent advancements in differential equations and control processes [9]. The validated model provides significant insights for the design and optimization of public health interventions, particularly in determining the timing of control measures. The findings can serve as a guide for policymakers, informing decisions aimed at mitigating the impact of epidemics while minimizing socio-economic disruptions.

While the present study offers substantial insights, several areas merit further exploration.

- The integration of behavioral dynamics constitutes the initial element. Subsequent research endeavors may entail the incorporation of individual behavioral modifications, such as adherence to social distancing measures or vaccination acceptance, with the objective of augmenting the model authenticity. The employment of advanced neural network-based approaches, such as those utilized in correlation analysis [10], holds promise in the modeling of complex behavioral patterns.

- *Multi-region validation.* The extension of the model to multiple regions characterized by varying population densities and connectivity patterns has the potential to enhance its generalizability and applicability to a range of epidemic scenarios.
- Thirdly, a policy scenario analysis is warranted. A more extensive array of policy interventions, including targeted lockdowns and travel restrictions, could offer more nuanced guidance for epidemic control. The application of deep learning techniques [11, 12] holds potential for the optimization of policy implementation strategies within dynamic environments.

In summary, the present study proposes a comprehensive theoretical model for understanding and optimizing epidemic spread in heterogeneous networks. The integration of theoretical simulations with real-world validation provides a valuable framework for public health decision-making, particularly in the context of balancing epidemic control with socioeconomic recovery.

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