Dynamic Epidemic Propagation in Community-Structured Networks

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Introduction

- **Epidemic modeling** has become a crucial tool for understanding and managing disease outbreaks.
- In modern societies, **community structures** play a significant role in shaping disease transmission dynamics.
- **Network theory** provides a powerful framework to capture these dynamics by modeling the underlying social interactions.
- This study focuses on the use of **Stochastic Block Models (SBM)** to simulate networks with distinct community configurations:
  - Sparse (minimal inter-community connections)
  - Balanced (moderate inter-community connections)
  - Dense (high inter-community connections)

Introduction

- Epidemics spread faster in **highly interconnected networks**, potentially overwhelming healthcare systems.
- Understanding how **network topology influences epidemic progression** can help design better containment strategies.
- The dynamic **SIR model** used in this study:
  - Captures real-world behavioral adaptations (e.g., social distancing).
  - Incorporates an adaptive **transmission rate** based on the current epidemic state.
- The goal is to provide **quantitative insights** into the relationship between network structures and epidemic dynamics, aiding policymakers in designing effective interventions.

Methodology: Network Structures

- **Stochastic Block Model (SBM):**
  - Models networks with community structures by adjusting connection probabilities.
  - Captures real-world network diversity:
    - **Sparse Networks**: Low inter-community interaction.
    - **Balanced Networks**: Moderate inter-community interaction.
    - **Dense Networks**: High inter-community interaction.
- **Adjacency Matrix Representation:**

$$\mathbf{P} = \begin{pmatrix} 0.1 & p \\ p & 0.1 \end{pmatrix}, \quad p \in \{0.001, 0.01, 0.05\}$$

where p represents inter-community connection probabilities.

Methodology: Network Structures

Figure 1: Stochastic Block Model Configurations

Methodology: Epidemic Model

- **Dynamic SIR Model Equations:**

$$\frac{dS}{dt} = -\tau(t)SI$$
$$\frac{dI}{dt} = \tau(t)SI - \gamma I$$
$$\frac{dR}{dt} = \gamma I$$

- **Dynamic Transmission Rate:**

$$\tau(t) = \max(0.1 \cdot \tau_0, \tau_0(1 - I_f)(1 - 0.5R_f))$$

  - τ_0: Base transmission rate.
  - $I_f(t) = \frac{I(t)}{N}$: Fraction of infected individuals.
  - $R_f(t) = \frac{R(t)}{N}$: Fraction of recovered individuals.
- Captures behavioral responses (social distancing) and herd immunity.

Results: Network Characteristics

- **Average Degree**:
  - Measures the average number of connections per node.
  - Dense networks exhibit higher values, leading to faster epidemic spread.
- **Average Path Length**:
  - Represents the average shortest path between nodes.
  - Dense networks have shorter paths, accelerating transmission.
- **Network Diameter**:
  - Maximum shortest path between any two nodes.
  - Sparse networks show higher diameters, indicating isolated clusters.
- **Assortativity**:
  - Indicates whether nodes prefer connecting with others of similar degree.
  - Minimal impact on epidemic spread but reveals structural nuances.

Results: Network Characteristics

Table 1: Network Topology Metrics

Metric	Sparse Inter	Balanced	Dense Inter
Average Degree	5.32	5.88	7.76
Average Path Length	3.73	2.98	2.45
Network Diameter	9	6	4
Assortativity (Degree Correlation)	0.012	-0.009	0.008
Number of Communities (Approx.)	2	2	2

Results: Epidemic Dynamics

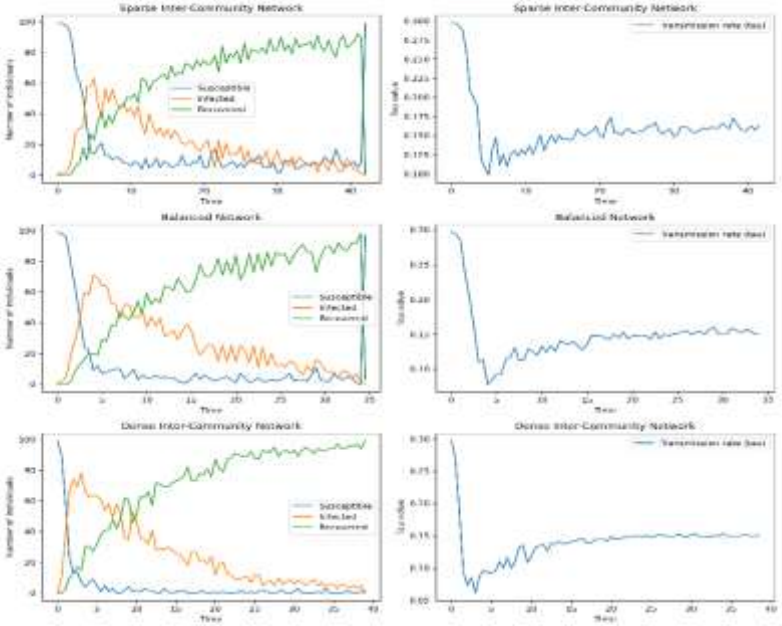
- **Peak Infection Rate:**
  - Dense networks exhibit the highest peak due to increased connectivity.
  - Sparse networks limit the spread, delaying and lowering the peak.
- **Time to Peak:**
  - Dense networks reach the peak faster, reducing time for interventions.
  - Sparse networks provide longer windows for containment measures.
- **Outbreak Size:**
  - Final outbreak size remains stable across network types, suggesting similar long-term impacts.

Results: Epidemic Dynamics

Table 2: Peak Infection Metrics Across Network Types

Metric	Sparse Inter	Balanced	Dense Inter
Peak Infection Metrics			
Mean Peak (%)	58.523	62.341	69.967
Std. Dev Peak	18.318	19.335	16.764
Median Peak (%)	64.0	68.0	74.0
Time to Peak (Time Steps)			
Mean Time	3.8995	3.1190	2.4945
Std. Dev Time	1.5549	1.2520	0.8983
Median Time	4.0	3.0	2.5
Outbreak Size Metrics (% Population Infected)			
Mean Outbreak	38.664	39.073	38.870
Std. Dev Outbreak	12.552	12.472	9.886
Median Outbreak	42.0	42.5	41.0

Epidemic Dynamics



Conclusion

- Network structure significantly influences the dynamics of epidemic spread.
- **Dense networks** lead to faster, more intense outbreaks.
- **Sparse networks** delay the spread, offering critical containment opportunities.
- These insights can guide **public health strategies**, optimizing intervention timing and targeting.

References

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Thank You