Frontiers of Dynamical Systems

PATTERNS OF ROOSTING IN A COLONY OF BATS BASED ON STATE-DEPENDENT DECISIONS, BENEFITS, AND COSTS

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Benefits and costs of social behaviors, governing rules

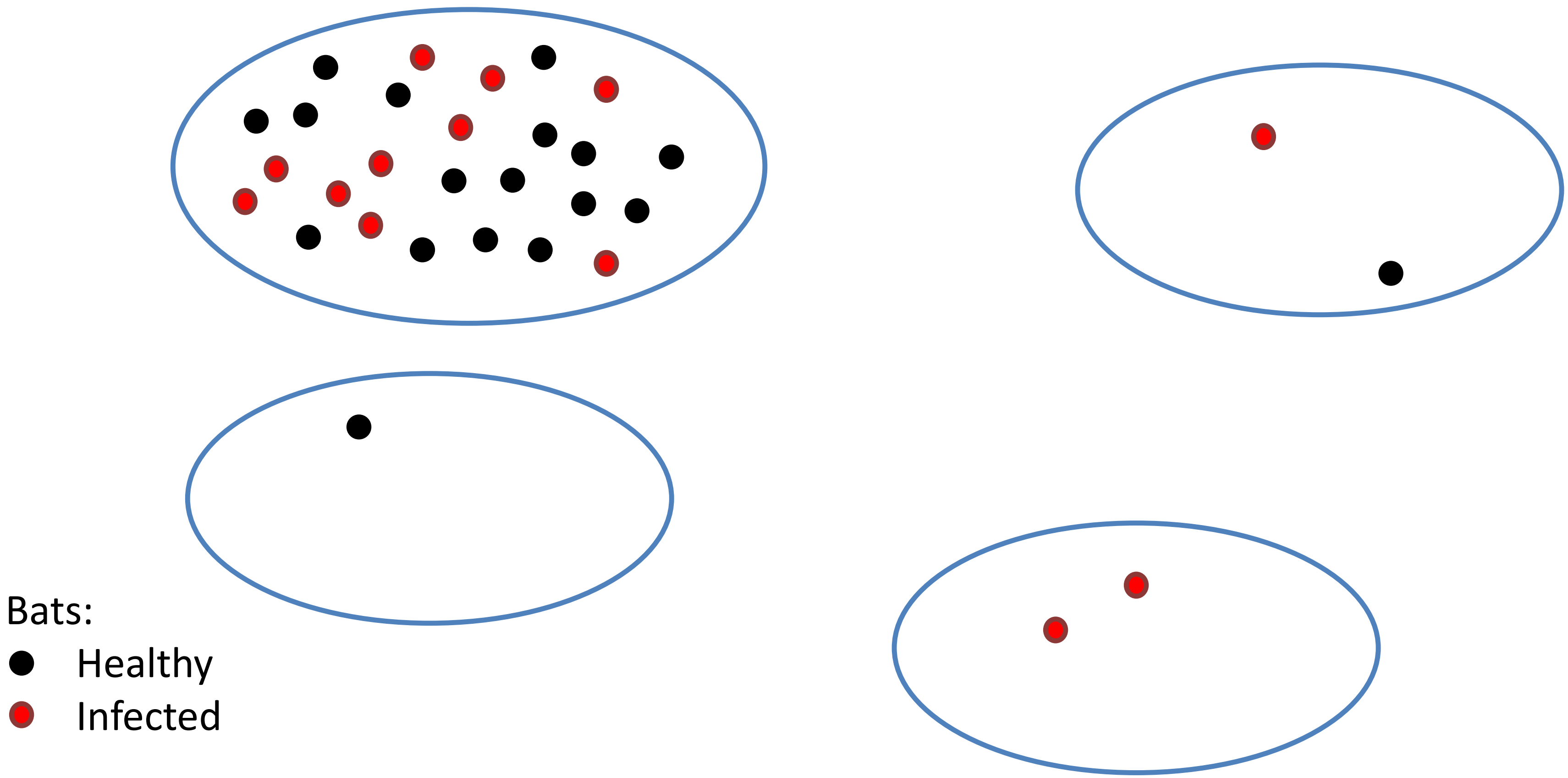
- Balance of maximized individual benefits and minimized costs,
  - Benefits: temperature, avoiding predators, stream of data, energy efficiency, …
  - Costs: lack of food, diseases, limited space, …



- Social dynamics, a time varying system that follows SIMPLE rules on the individual scale and shows complex behavior on the group scale

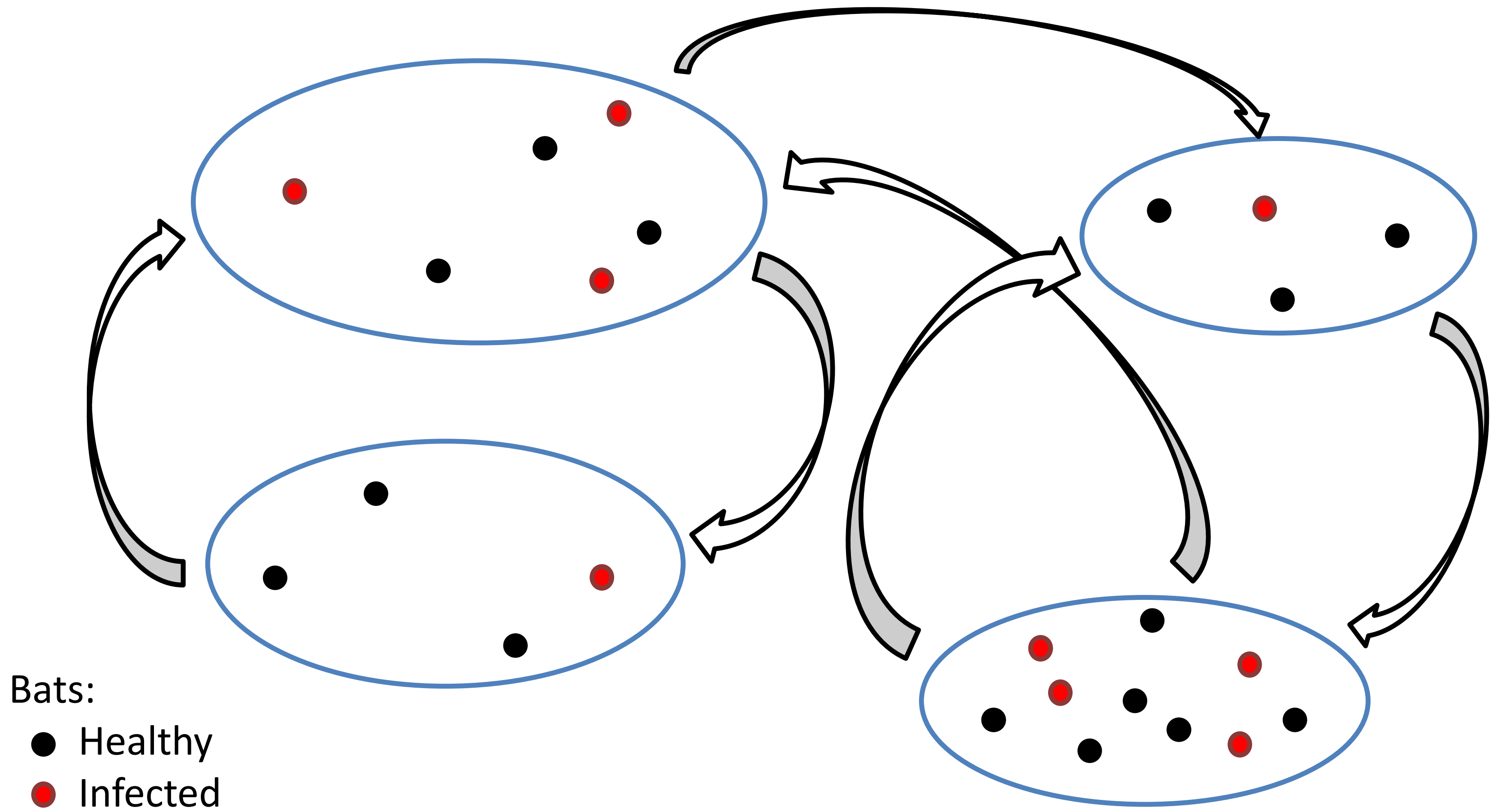
Social behavior; Dynamics of roost selection

- **Settlement**: long term stay of almost all the colony population in one roost,



Social behavior; Dynamics of roost selection

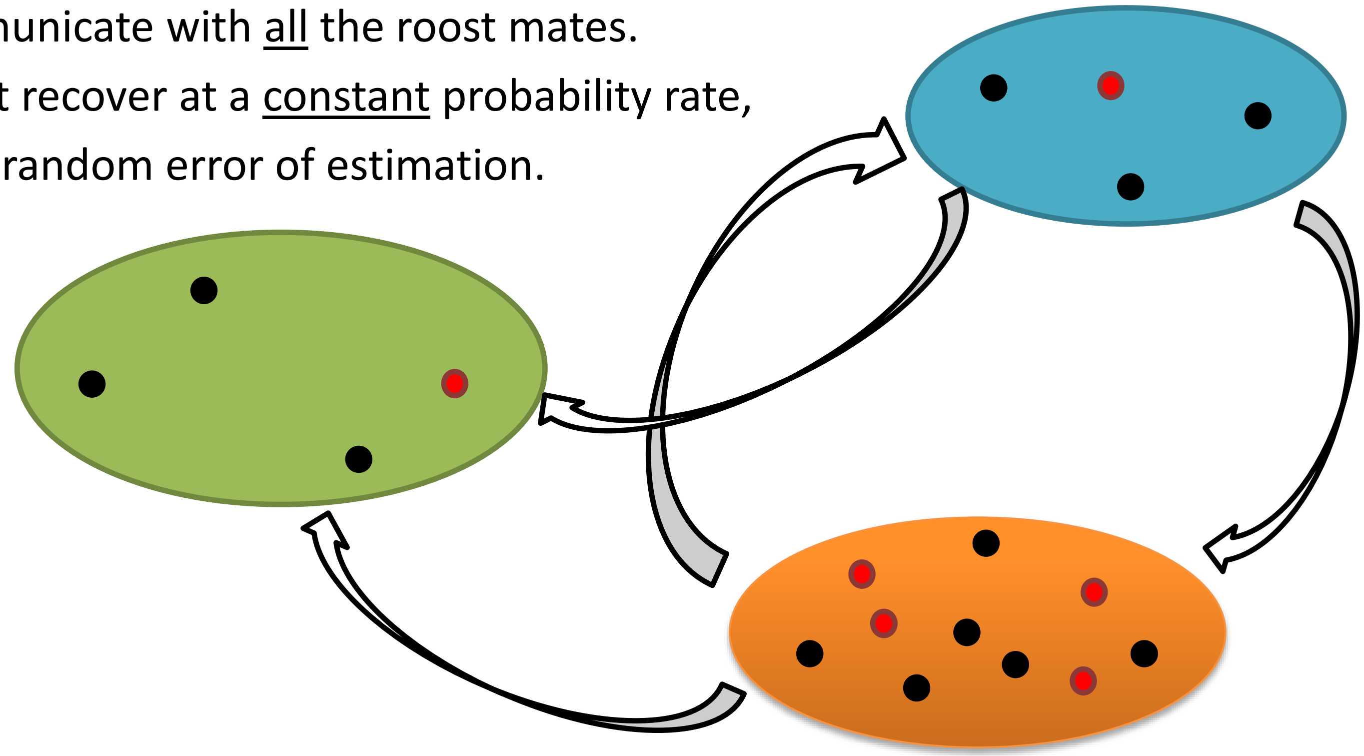
- **Fission-fusion**: the cycles of dividing/splitting and joining together of individuals.



Modeling

Mathematical model

- ***Kashima model***: balancing the conflicting needs of maximizing information accuracy and minimizing infection risk.
  - Each roost has a constant non-normalized quality.
  - Each individual bat has its estimation of some other roosts,
  - Each bat communicate with all the roost mates.
  - An infected bat recover at a constant probability rate,
  - Each bat has a random error of estimation.



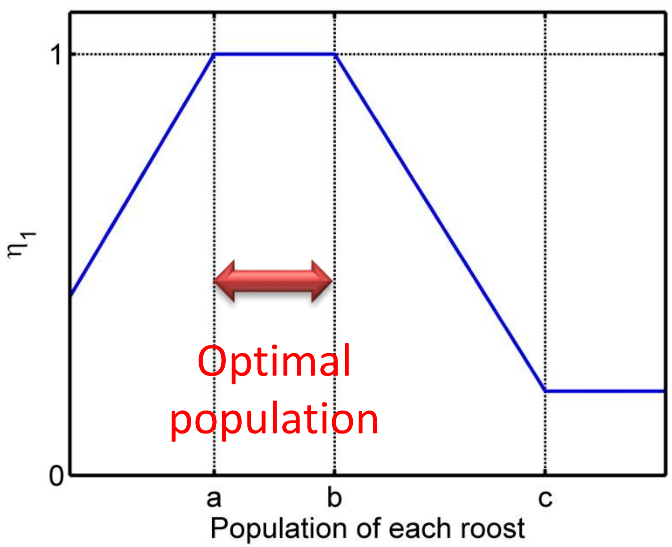
Bats:
- Healthy
- Infected

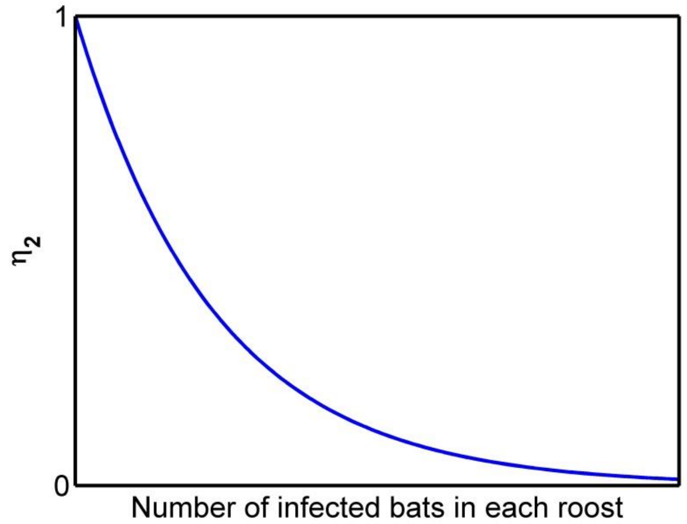
<u>Mathematical model</u>

- ***Our modifications:***
  - Roost quality is a **<u>state dependent</u>** function:
    - Inherent condition of the roost, roost population, density of infected bats
  - Each individual randomly communicates with **<u>limited</u>** number of roost mates and out-roost individuals,
  - Each individual updates its knowledge about the other roosts quality based on its own experiences and communication results,
  - Each bat has a random error of estimation about its living roost,
  - Health status changes: two different paths:
    - Healthy to infected: probability of change depends on the short term history of stayed roosts,
    - Infected to healthy: two stage,
      - a) convalescence (remedial period),
      - b) period of dependency to the health condition of selected roosts

Roost state dependent quality

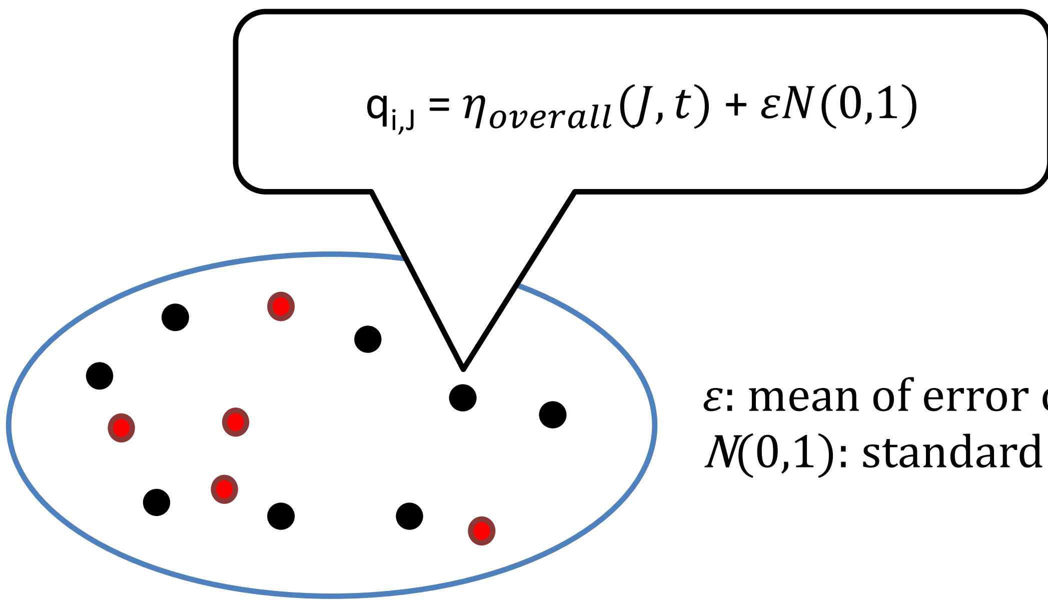
- Roost quality is a function of:
  - inherent condition, e.g., ventilation: $\eta_{inherent}$
  - Population: η_1
  - density of infected bats: $\eta_2 = e^{-\alpha infect_{ed}}$
  - $\eta_{overall} = \eta_{inherent}\, \eta_1\, \eta_2$





Roost quality perception

- Perception of each individual about its own roost,



ε: mean of error of estimate
$N(0,1)$: standard normal distribution

Bats:
- Healthy
- Infected

Roost quality, probabilistic roost selection

- Perception of all individuals about all the roost,

$$Q = \begin{bmatrix} q(1,1) & \cdots & q(1,R) \\ \vdots & q(i,j) & \vdots \\ q(N,1) & \cdots & q(N,R) \end{bmatrix}$$

- Learning mechanism:

$$q_{i,j=1..R,\neq J}(t+1) = \alpha . \underbrace{q_{i,j=1..R,\neq J}(t)}_{\text{One's old data}} + (1-\alpha) . \underbrace{\tilde{q}_{i,j=1..R,\neq J}(t)}_{\text{New data from the other agent}}$$

- Probabilistic switching between roosts (nonlinear weighting):

$$p_k = \frac{e^{\beta q_k}}{\sum_{j=1}^{R} e^{\beta q_j}}$$

- Spatial aggregation (Morisita) index:

$$I = \frac{\sum_{j=1}^{R} n_j(t) . n_j(t-1)}{N(N-1)}$$

Probabilistic dynamics of health condition

A healthy bat

- **remains healthy**
- **becomes infected**

Health condition of previous roosts

An infected bat

- **remains infected;** convalescence
- **becomes healthy;** susceptible to the health condition of selected roost.

Random infection rate: changing the status of each healthy individual to infected at each time step; external forcing parameter,

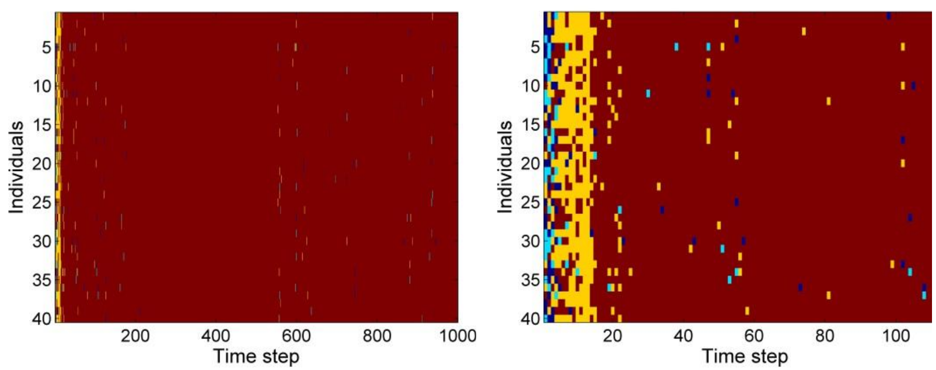
Health condition of each roost: proportional to the density of healthy population

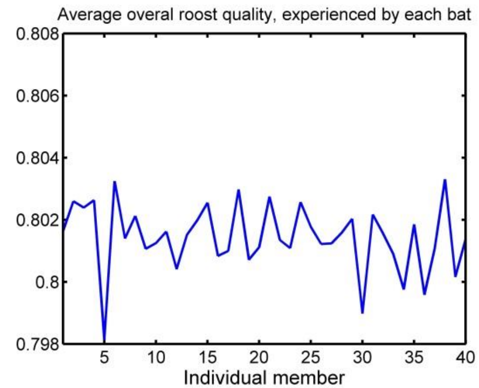
Results

(A1) Settlement

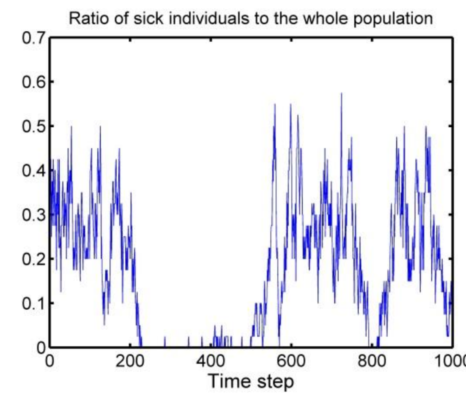
- (A1) Intelligent roost selection yields individual benefits.

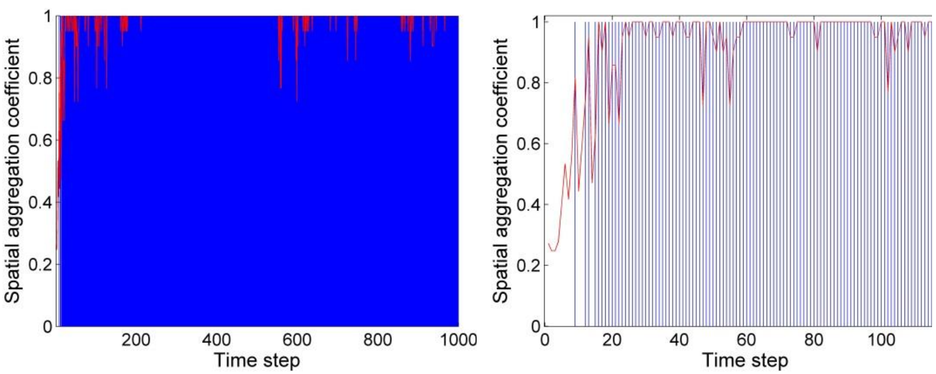
N = 40, R = 4, $\boldsymbol{\beta = 20}$, $\gamma = 0.1\%$, initial sickness ratio $= 20\%$

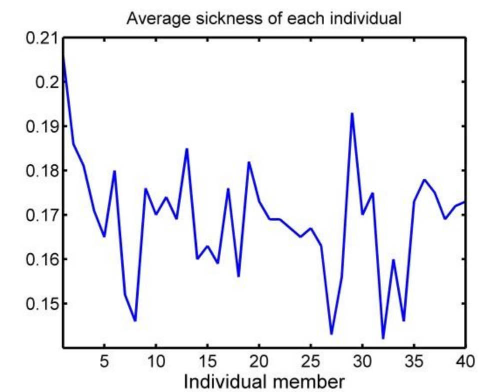




Roost selection





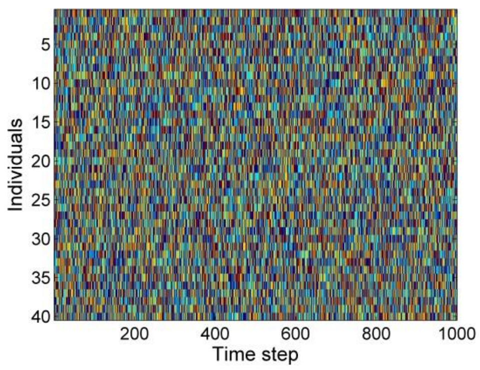


Morisita index, fusion cases

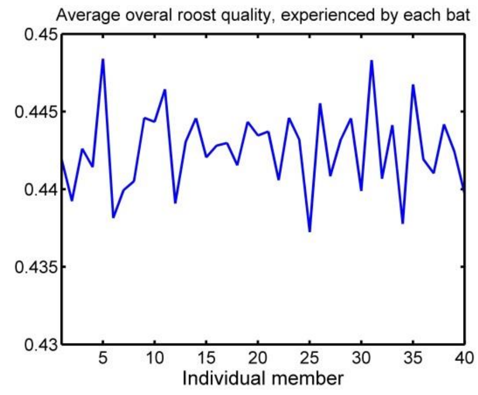
(A2) Random motion

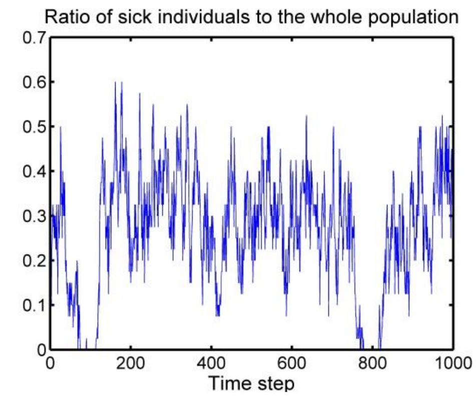
- (A2) Random roost selection.

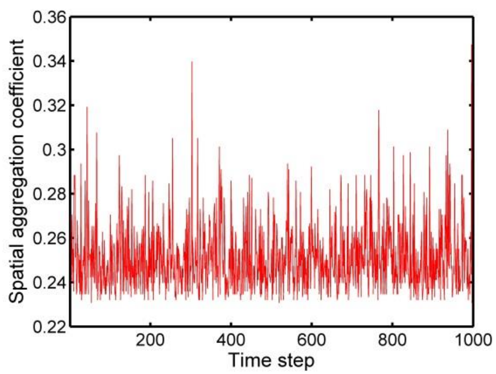
N = 40, R = 4, $\boldsymbol{\beta = 0}$, $\gamma = 0.1\%$, initial sickness ratio $= 20\%$



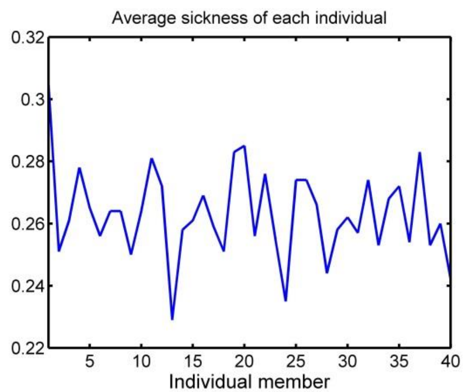
Roost selection







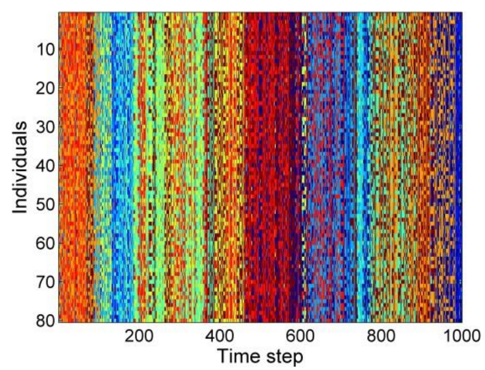
Morisita index



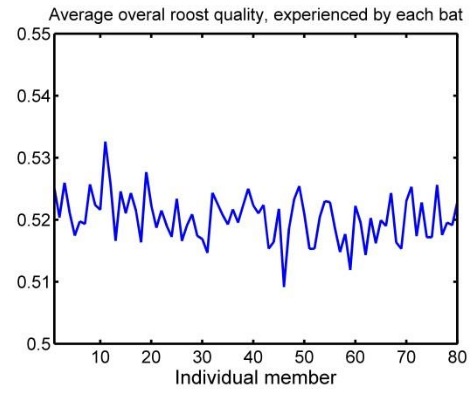
(C1) Fission-Fusion

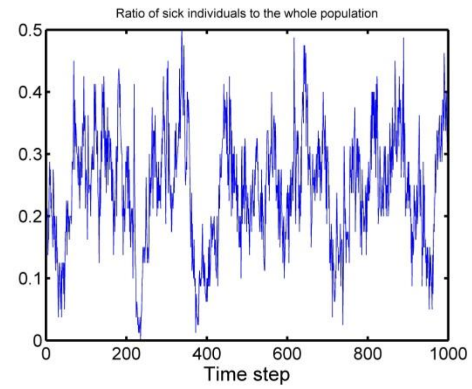
- (C1) Intelligent roost selection yields individual benefits.

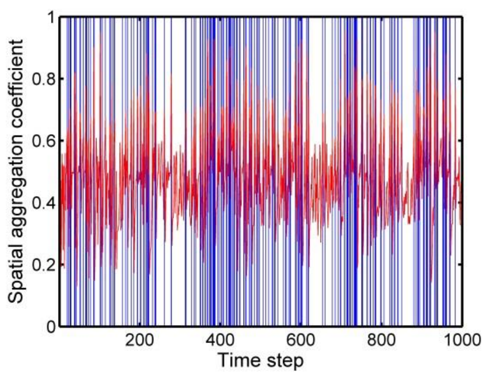
N = 80, R = 8, $\boldsymbol{\beta = 20}$, $\gamma = 0.1\%$, initial sickness ratio $= 20\%$



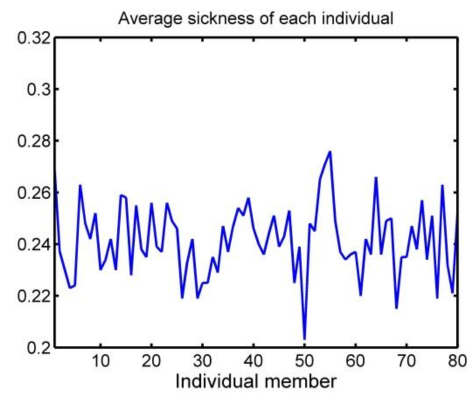
Roost selection







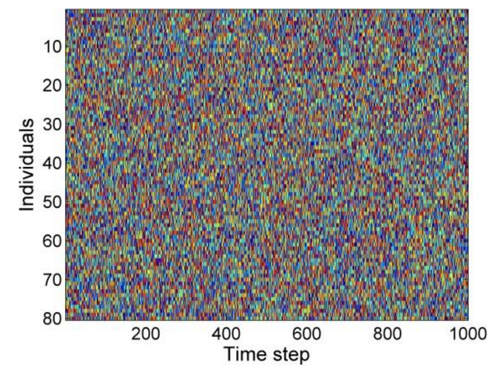
Morisita index



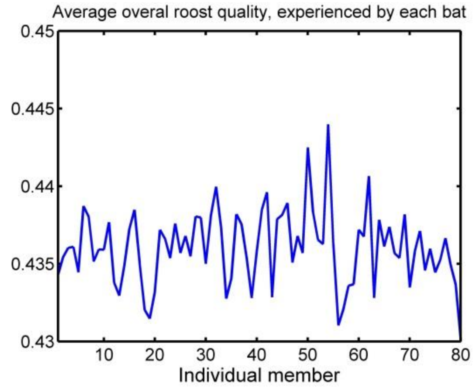
(C2) Random motion

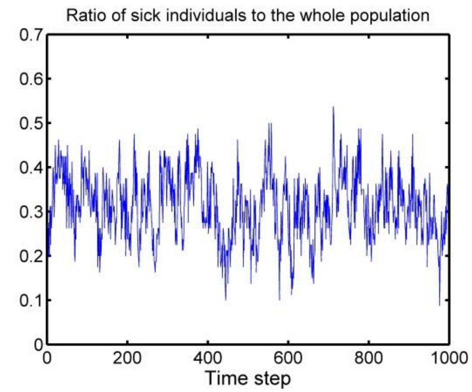
- (C2) Random roost selection.

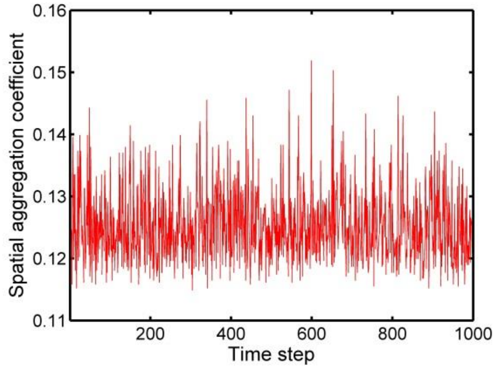
N = 80, R = 8, $\boldsymbol{\beta = 0}$, $\gamma = 0.1\%$, initial sickness ratio $= 20\%$



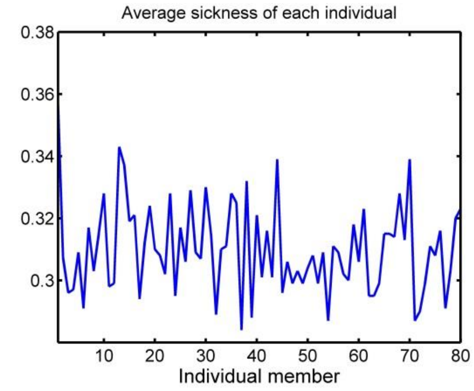
Roost selection







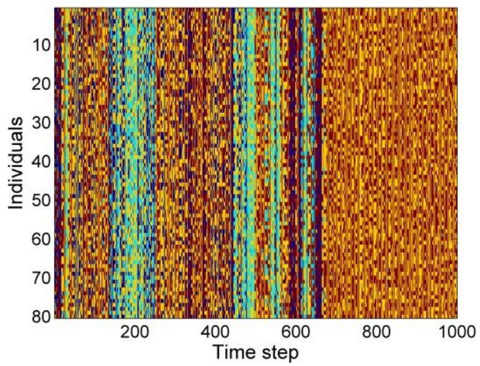
Morisita index



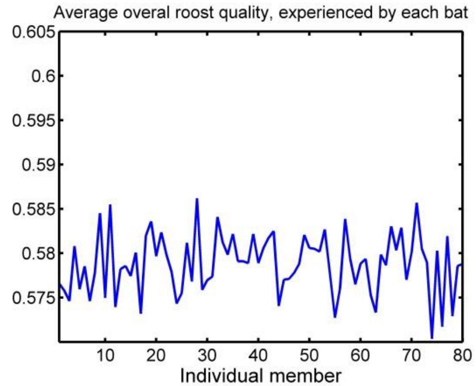
(D) Fission-Fusion

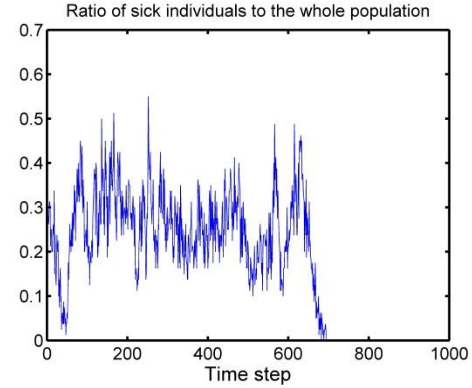
- (D) Intelligent roost selection, **zero external infection rate**

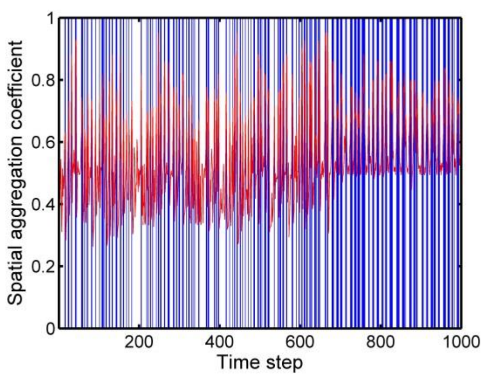
N = 80, R = 8, $\boldsymbol{\beta = 20}$, $\gamma = 0$, initial sickness ratio $= 20\%$



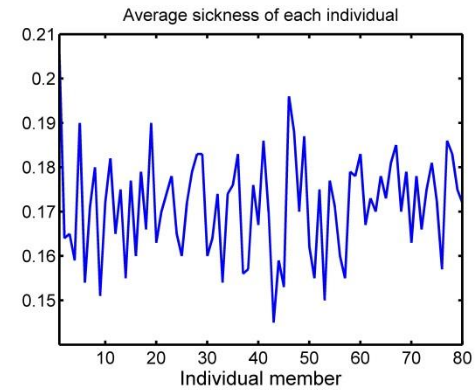
Roost selection



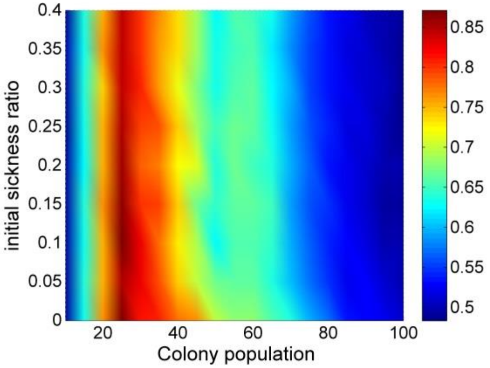




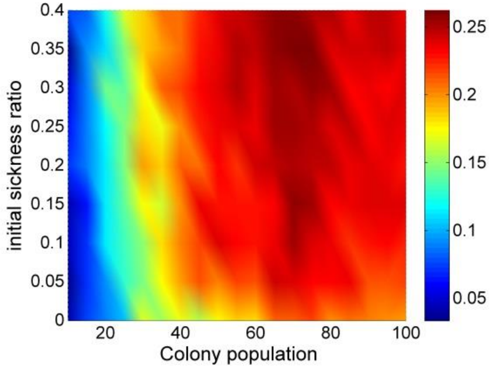
Morisita index



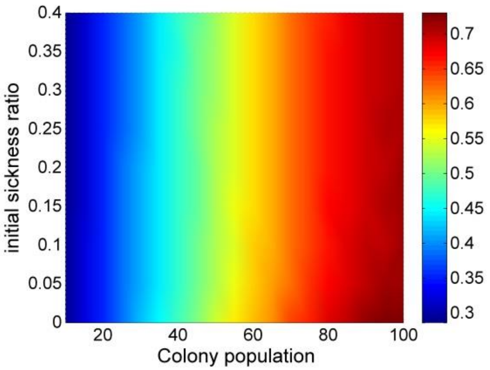
Averaged behavior



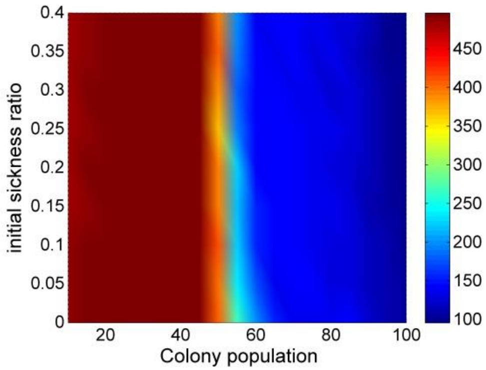
Average of all bats' overall roost quality experiences, $\beta = 20$.



Average of all bats overall sickness experience, $\beta = 20$.



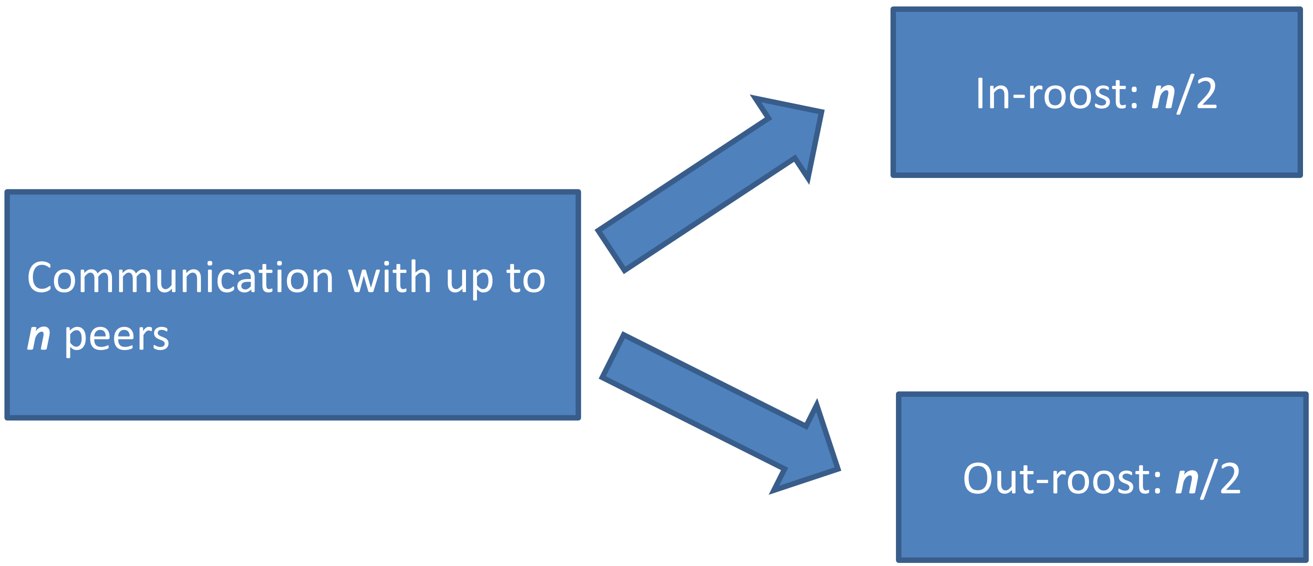
Average of all bats' overall roost quality experiences, $\beta = 0$.



average number of fusion cases , $\beta = 20$.

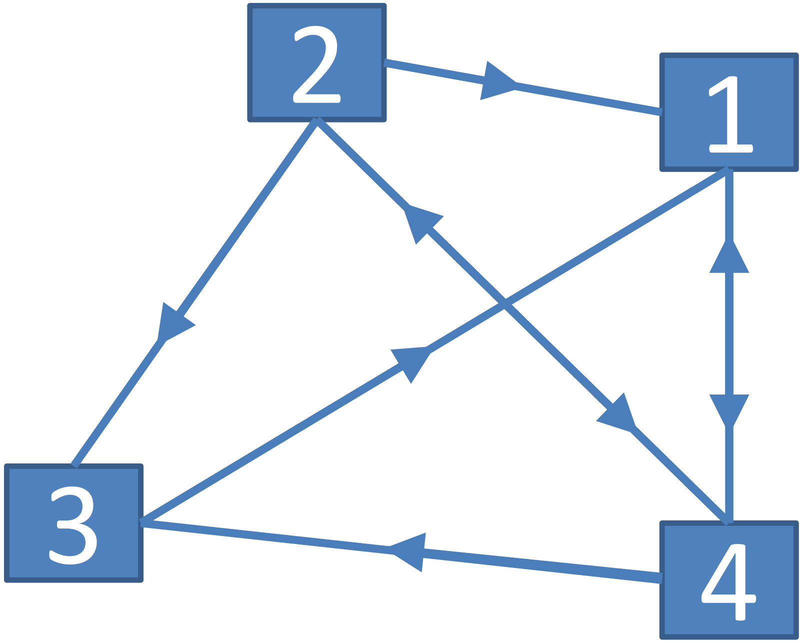
Network Properties

Numerosity constraint on the bat communication



✓ Gaussian distribution

Communication network

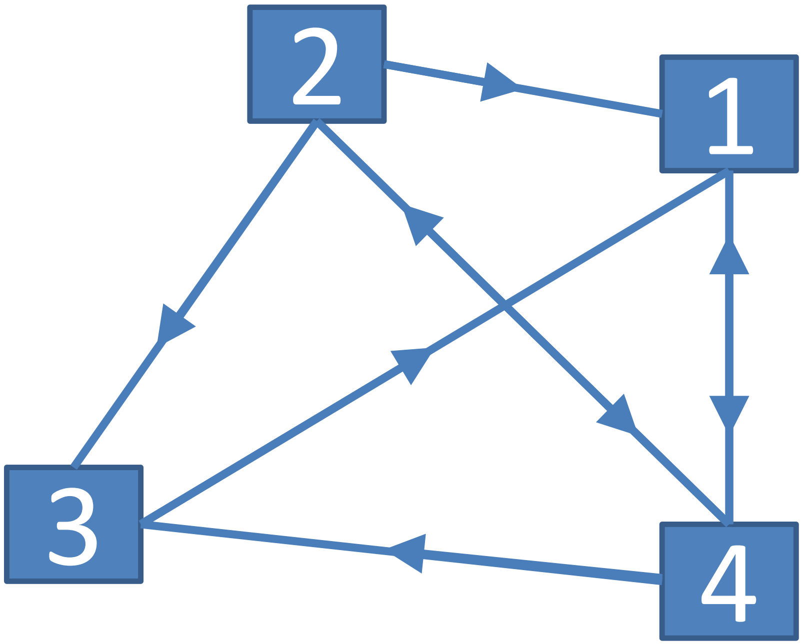


Rectangular: bats

Arrows: directed communication

Directed network of bat communication for N = 4

Network matrices



$$A = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 3 \end{bmatrix}$$

$$L = D - A = \begin{bmatrix} 1 & 0 & 0 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & 0 & 1 & 0 \\ -1 & -1 & -1 & 3 \end{bmatrix}$$

Network coarse observables

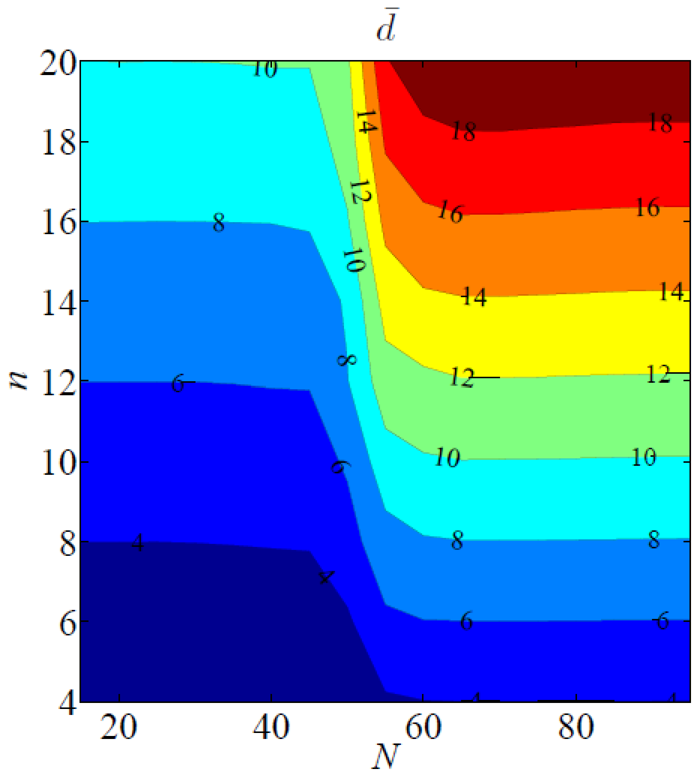
- **Degree**
- **Clustering coefficient**
- **Betweenness centrality**

Degree

$d_i(t)$: the diagonal element of the matrix D

- ✓ The number of peers that a bat communicates with
- ✓ Individual centrality

Degree - results



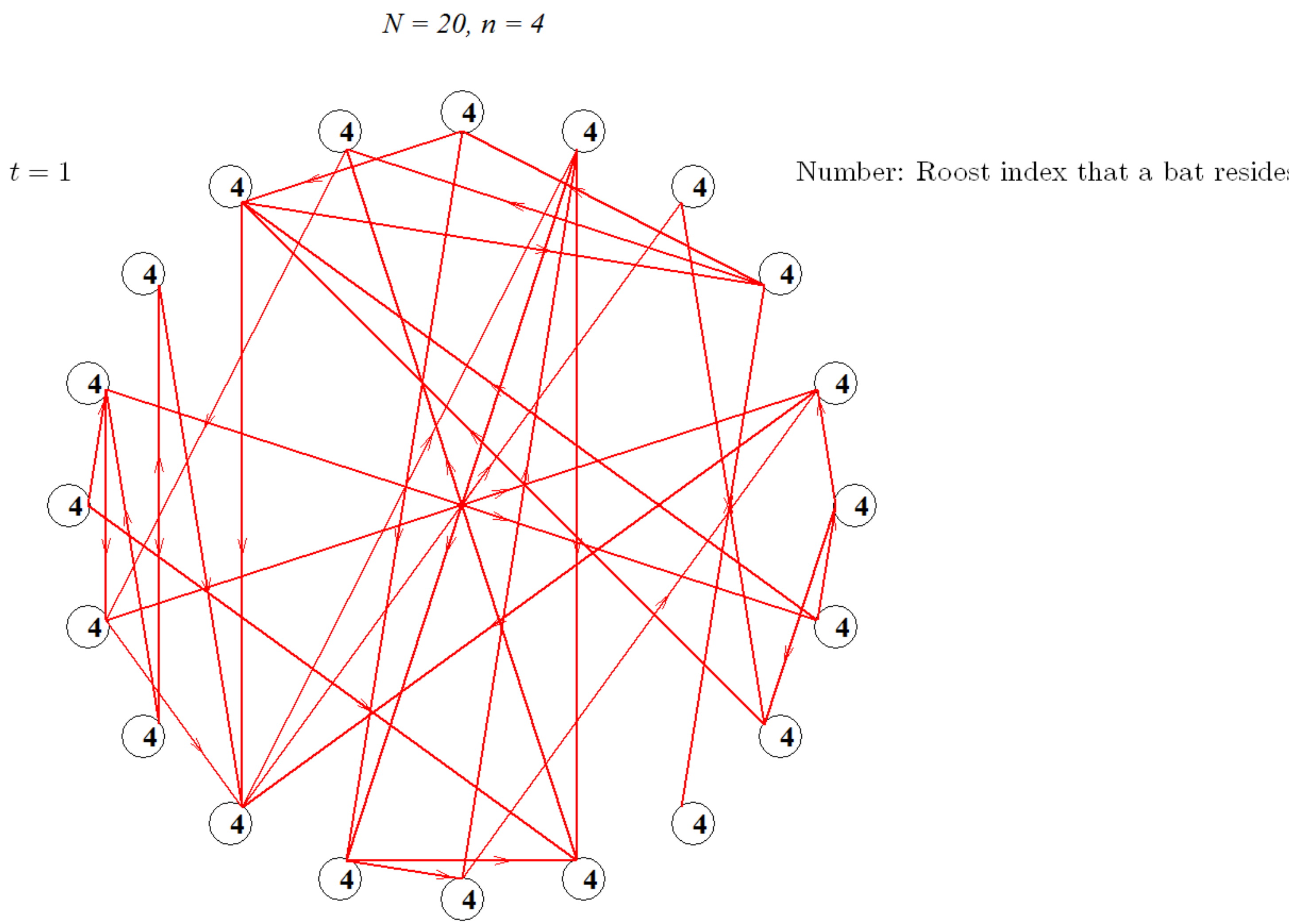
***Horizontal* axis**: the number of bats

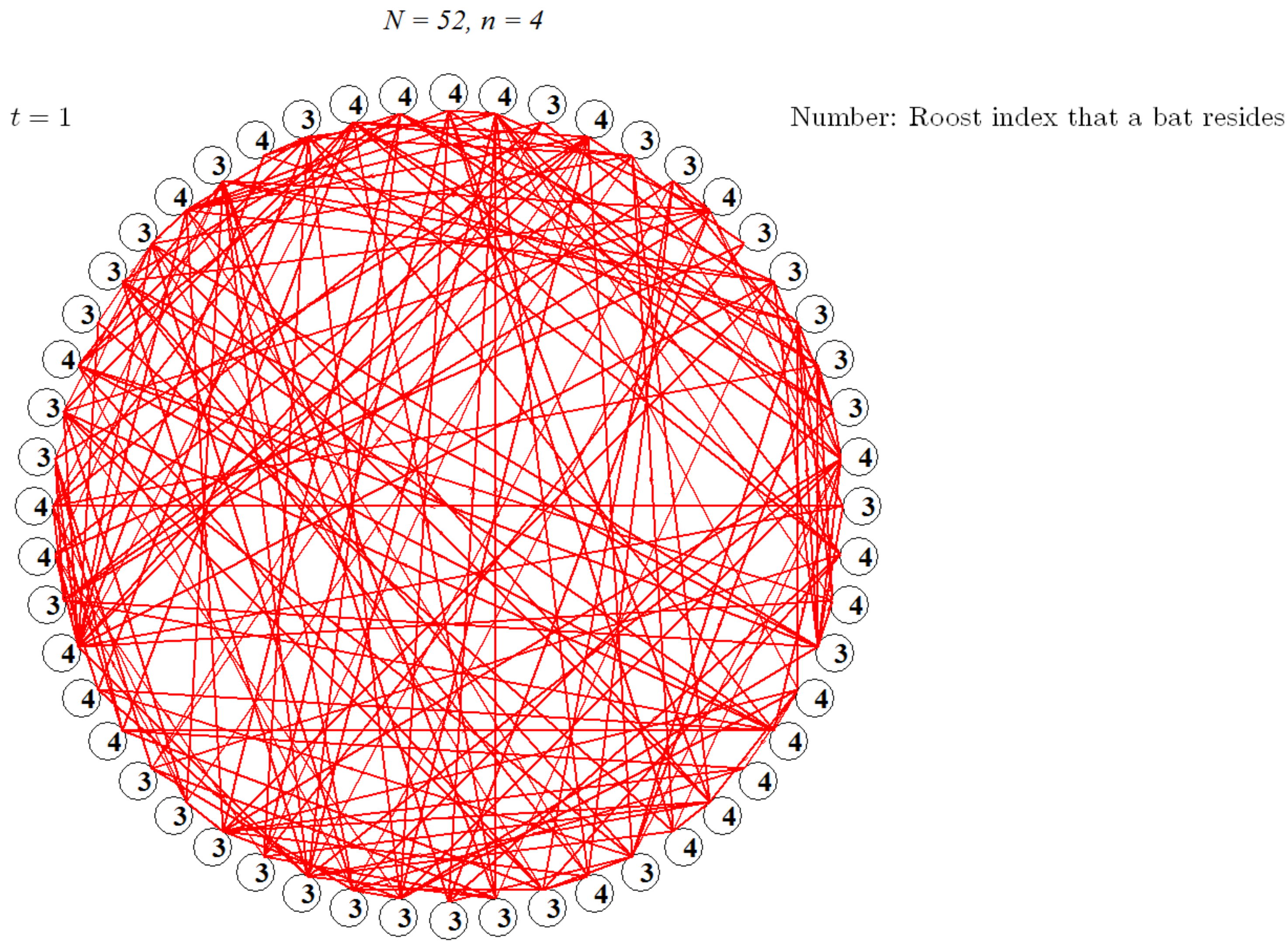
***Vertical* axis**: the numerosity constraint

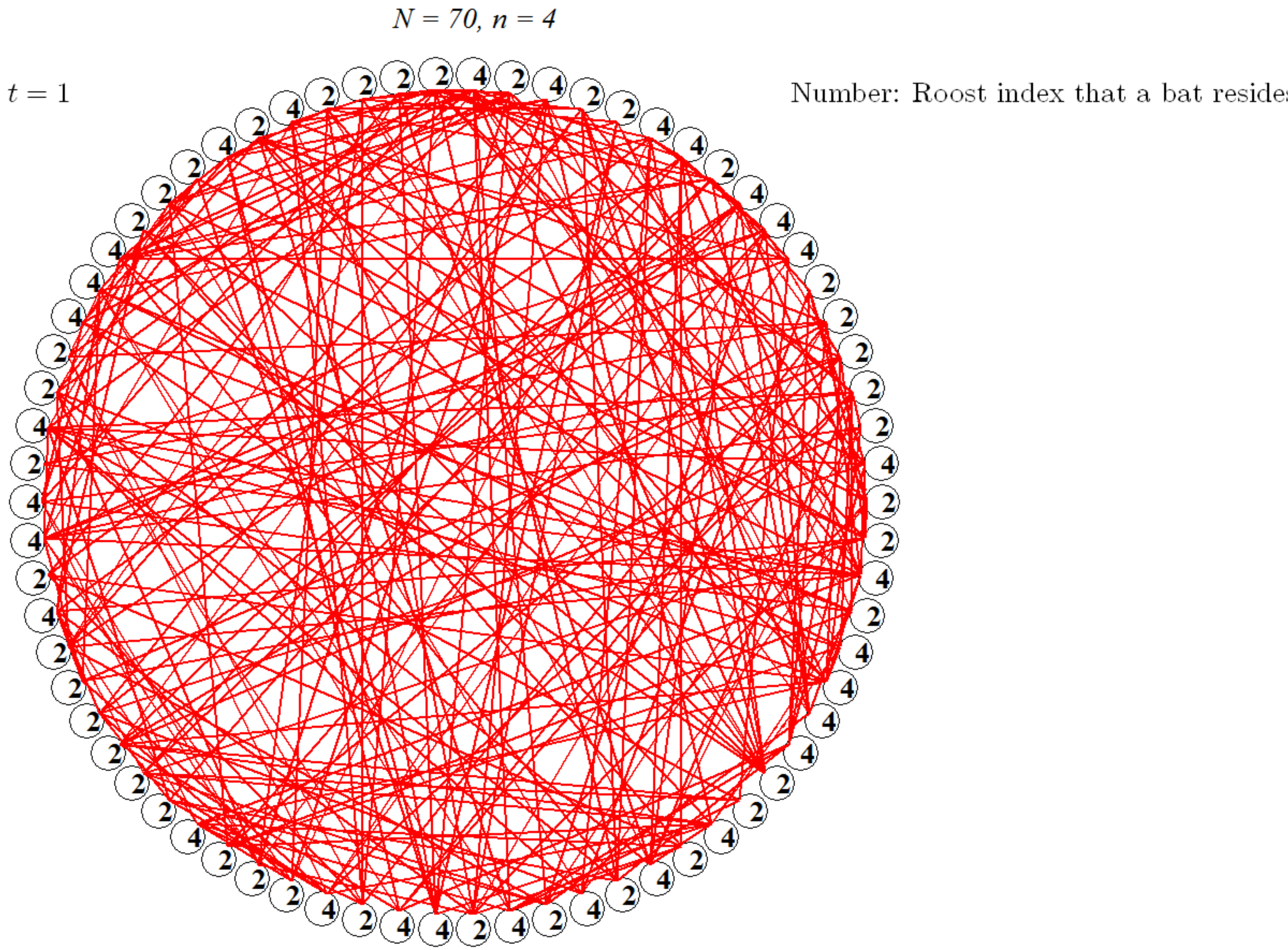
N<45: settlement behavior

45<N<60: fission-fusion behavior

N>60: fission behavior


N = 20, n = 4
$t = 1$
Number: Roost index that a bat resides
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4
4


N = 52, n = 4
t = 1
Number: Roost index that a bat resides


N = 70, n = 4
t = 1
Number: Roost index that a bat resides

Clustering coefficient

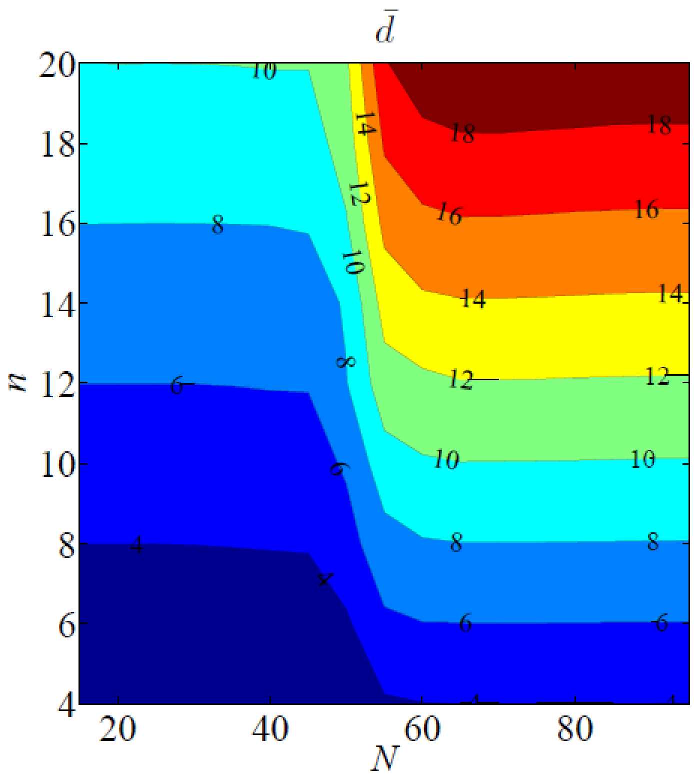
$$c_i(t) = \frac{e_i(t)}{k_i(t)(k_i(t) - 1)}$$

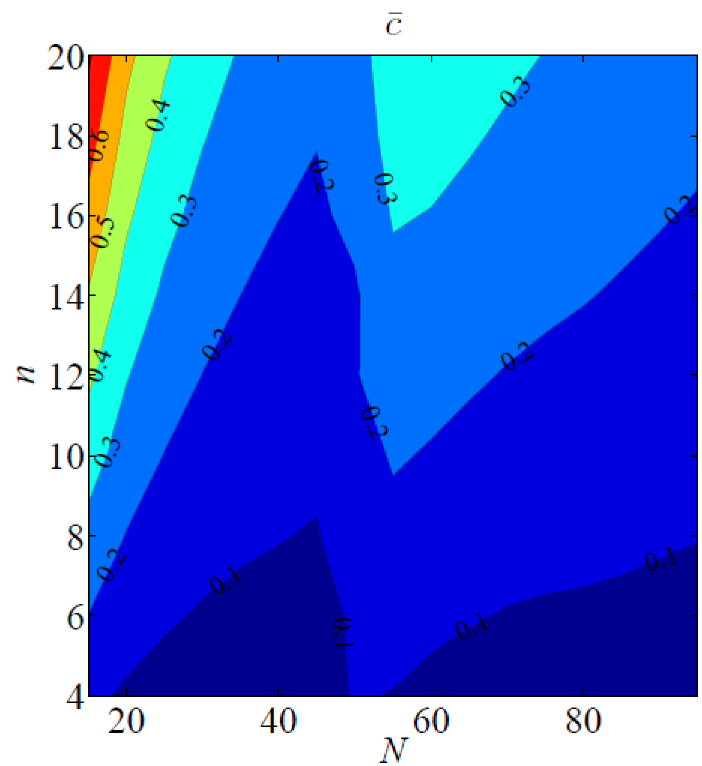
$e_i(t)$: the actual number of connections among bat *i*'s neighbors;

$k_i(t)$: the number of bat *i*'s neighbors

✓ the extent of clustering/friendship

Clustering coefficient - results





Betweenness centrality

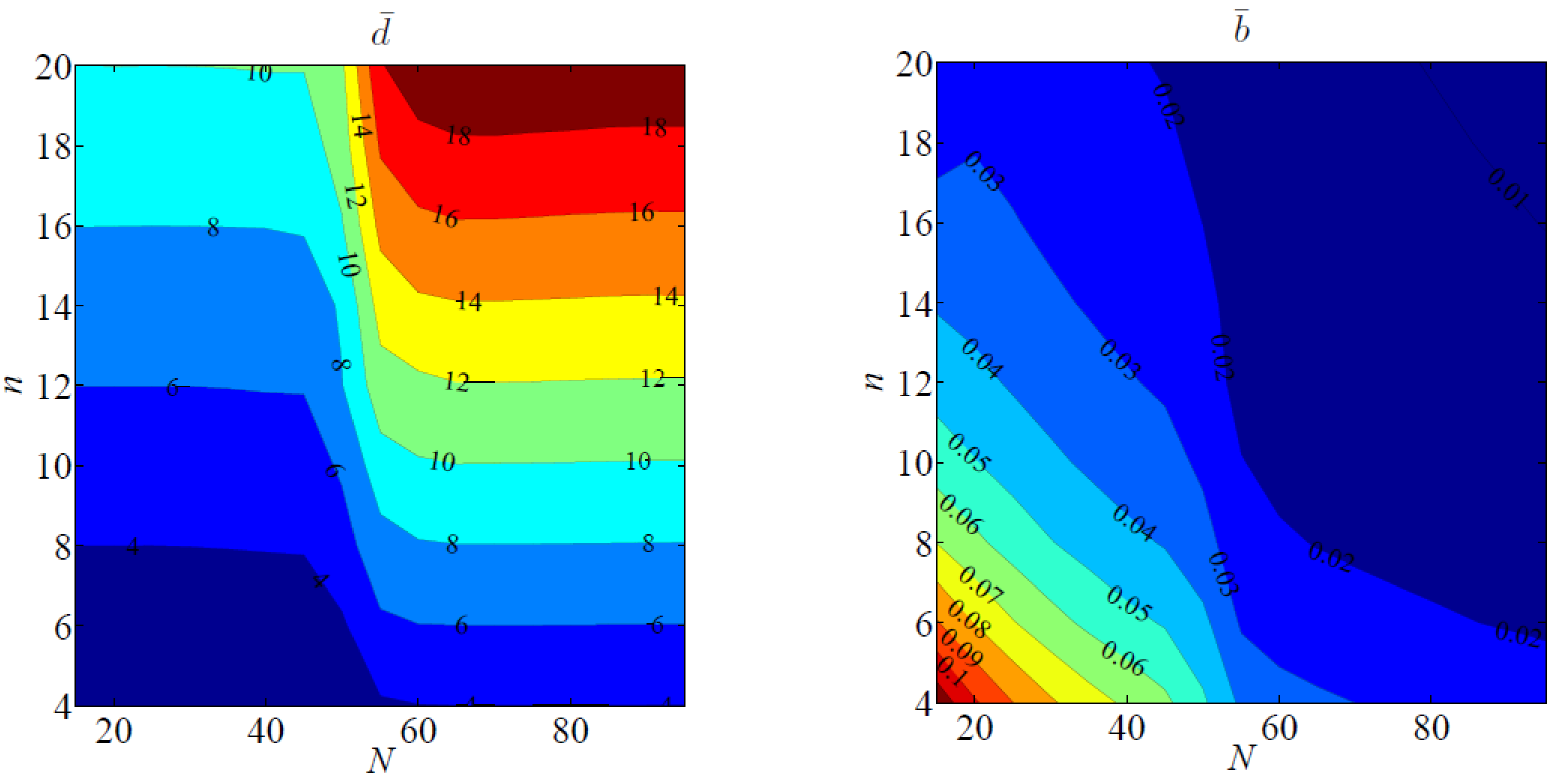
$$b_i(t) = \frac{1}{(N-1)(N-2)} \sum_{i \neq j \neq k} \frac{s^i_{jk}(t)}{s_{jk}(t)}$$

$s_{jk}(t)$: the number of shortest paths between bat j and bat k

$s^i_{jk}(t)$: the number of shortest paths between bat j and bat k that contain bat i

✓ Individual importance in connecting others

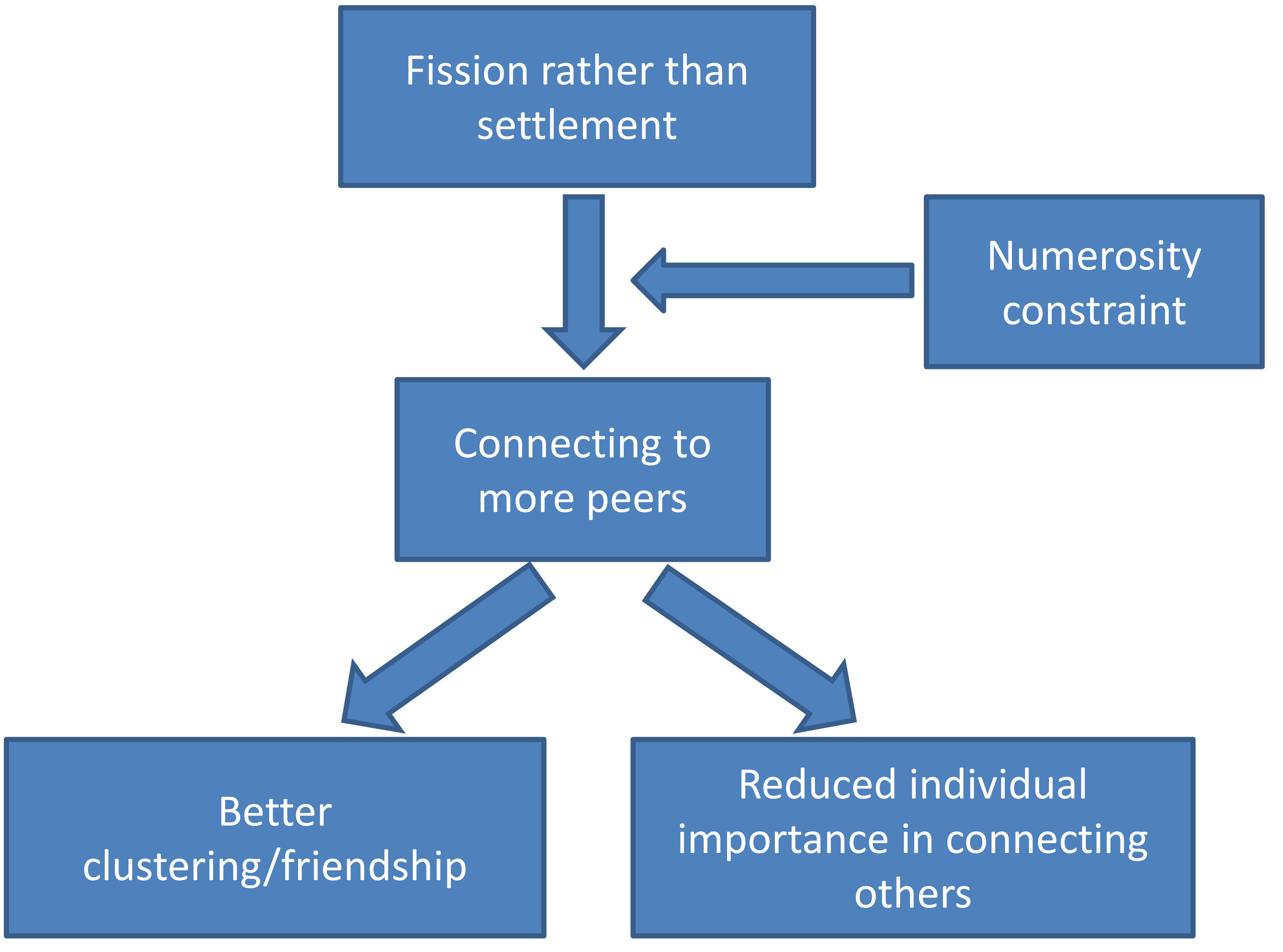
Betweenness centrality - results



Conclusions

- The optimum population range has a big influence on the behavior of the colony. If the colony size is close to that rage, we would expect settlement behavior to happen. In this condition each member of the colony would obtain more benefits than if staying roosts is selected randomly.
- If enough roosts are not available and/or the colony population is large, then intelligent roost selection would not be so beneficial.
- If the colony size is between these two limits and/or individuals have enough options of roosts, then fission-fusion behavior occurs.
- Overall behavior of the colony is not sensitive to the initial sickness ratio. The protocol of changing the health status stabilizes the number of infected individuals in a very short amount of time.
- There is a very distinct boundary between settlement and the fission-fusion (synchronized motion) behavior.
- External infection rate is a very important parameter in this model. If this rate is zero then we could observe infection-free colony, but if it is non-zero then the number of infected individuals would remain non-zero.

Conclusion of network properties



Future work

1. A weighted network with out-roost communication considered more important.

2. More network properties: shortest path length, assortativity.

Acknowledgement

The authors would like to thank Dr. Nicole Abaid for her kind mentorship and review of the paper.

Questions?

Thank you for your patience!
Go Hokies!!!