A Dynamic Patient Network Model of Hospital-Acquired Infections

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Motivation

The spread of infection is a significant problem, particularly in large, tertiary-care hospitals around the world

One approach: Ensure an adequate ratio of healthcare workers (HCWs) to patients

Objectives

- Examine the contact network of patients within a simulated hospital and determine how it affects transmission
- Quantify the effects of HCW behavior and patient turnover

Baseline Conceptual Model – Patient Network

Patients are connected by sharing a nurse and/or physician

Patient assignments can lead to various network configurations (i.e., densities) that affect transmission

Key parameters:

- Number of patients, nurses, and physicians
- Sharing configuration
- Cohort alignment

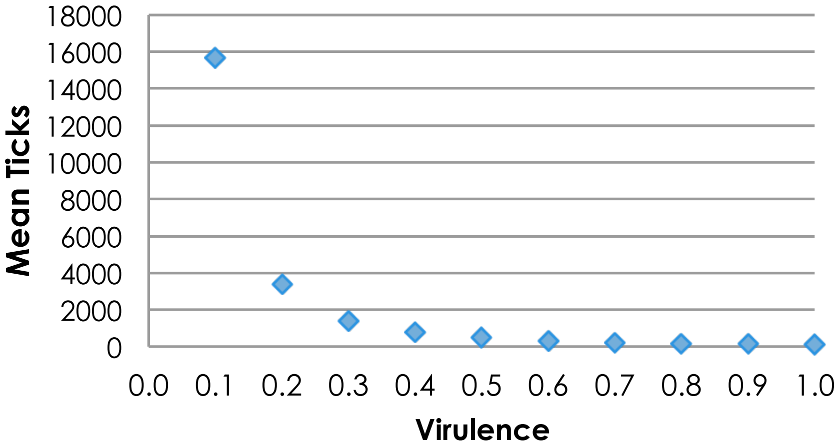
Conceptual Model – Transmission Dynamics

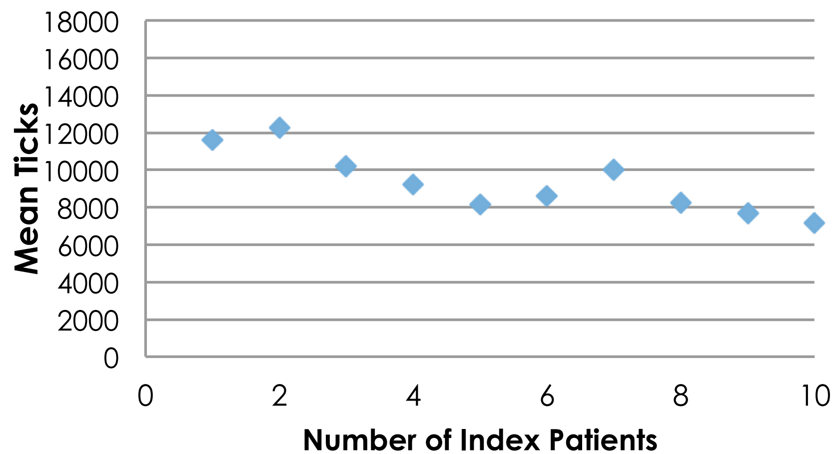
Transmission originates with index patient(s), who can transiently colonize an HCW

Transiently colonized HCWs can transmit to other patients

The pathogen can only spread along a network path between patients

<u>Key parameters</u>: *virulence, number of index patients*

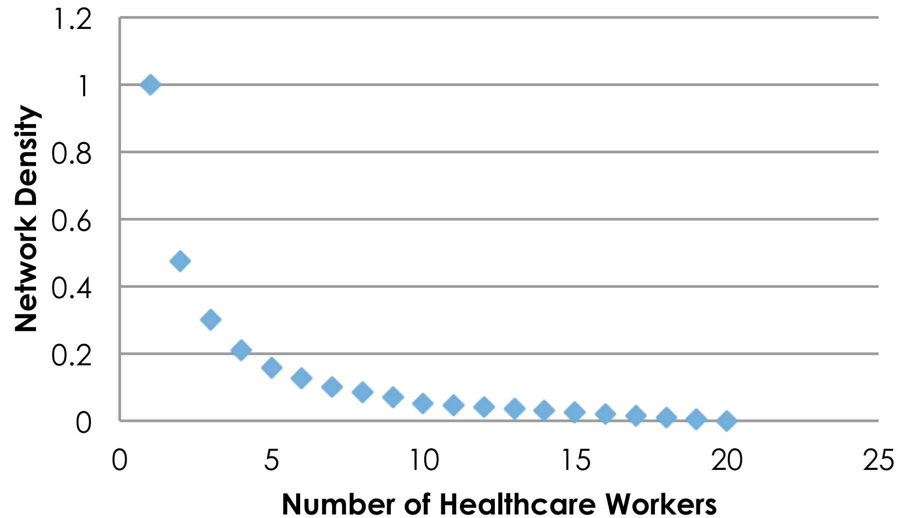




Network Density

Definition: Ratio of links in the network to the number of links in the complete network

$$d = \frac{\sum_k \binom{i_k}{2}}{\binom{n}{2}} \longrightarrow$$



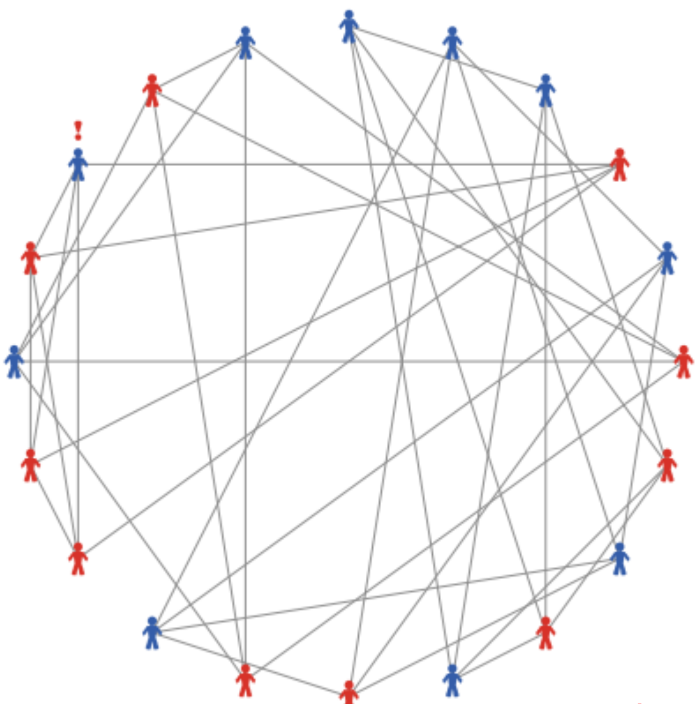
Example:

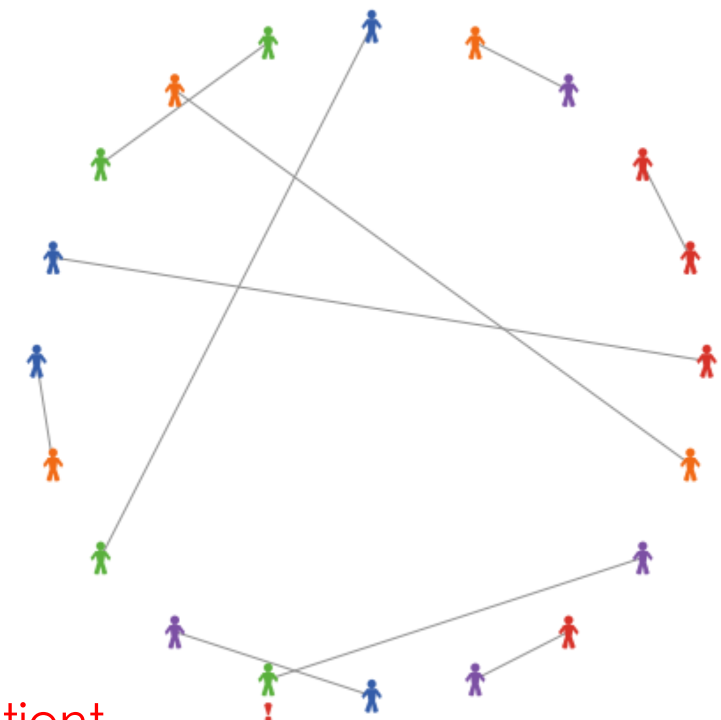
- 20-patient ICU with 10 nurses, 5 physicians
- Nurse density = 10(1)/(20(19)/2) = 0.0526
- Physician density = 5(4(3)/2)/(20(19)/2) = 0.1579

Patient Network Examples

Nurse Density = 0.2105 (4)
Physician Density = 0.4737 (2)
Total: 6 HCWs

Nurse Density = 0.0526 (10)
Physician Density = 0.1579 (5)
Total: 15 HCWs





! - Index Patient

How does density affect the speed of transmission?

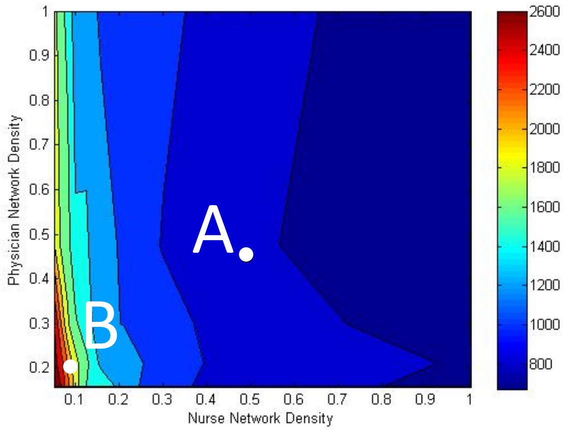
High density networks are extremely conducive to transmission

Transmission is strongly tied to the density of the nurse network

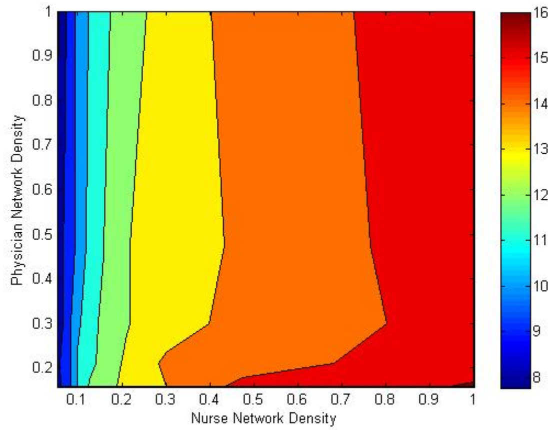
Nurses account for most transmissions when densities are high, but physicians pose a potentially more serious threat

- Physicians become the predominant source when nurse densities are low
- They can also spread to multiple nurse cohorts

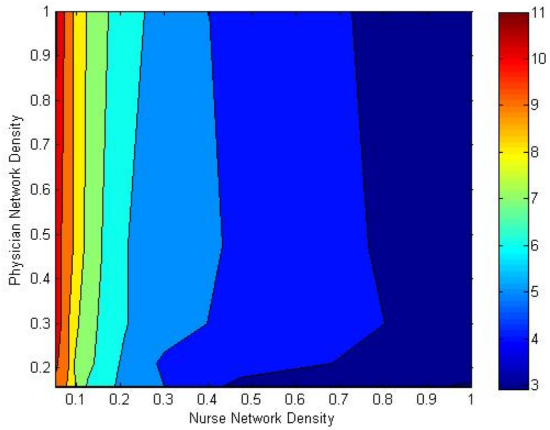
Mean Time to Transmission



Nurse Transmissions



Physician Transmissions

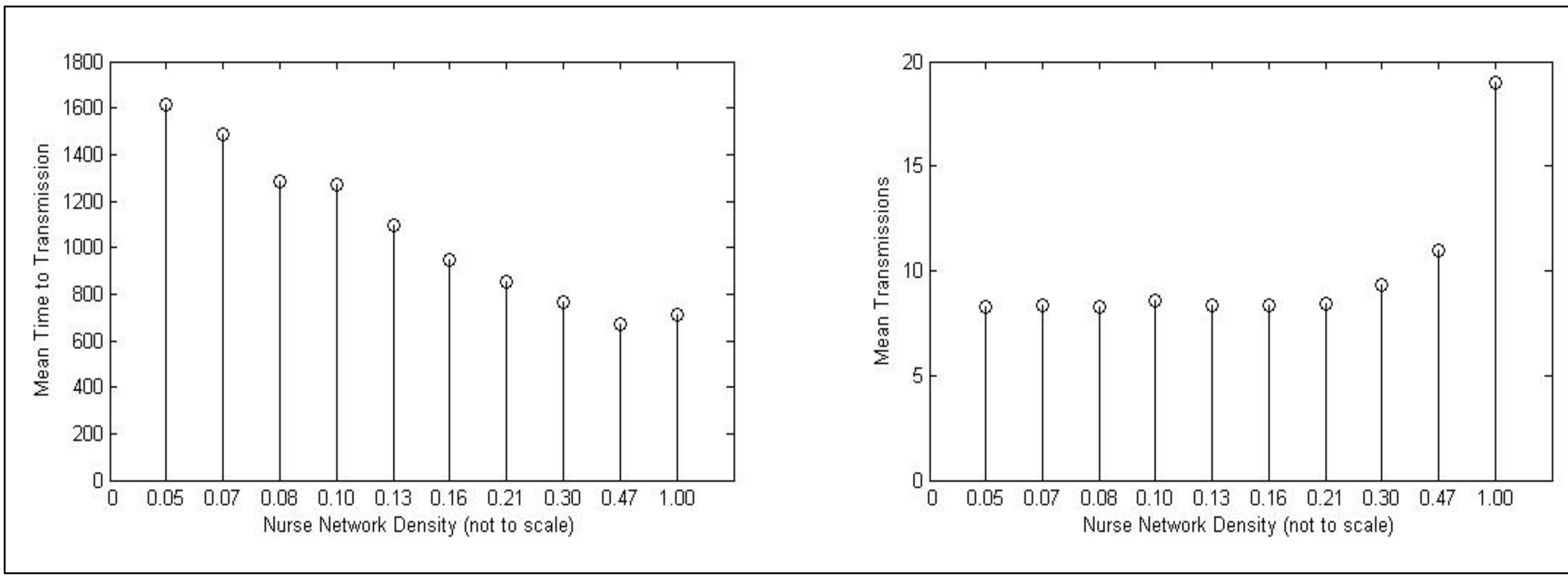


Cohort Alignment

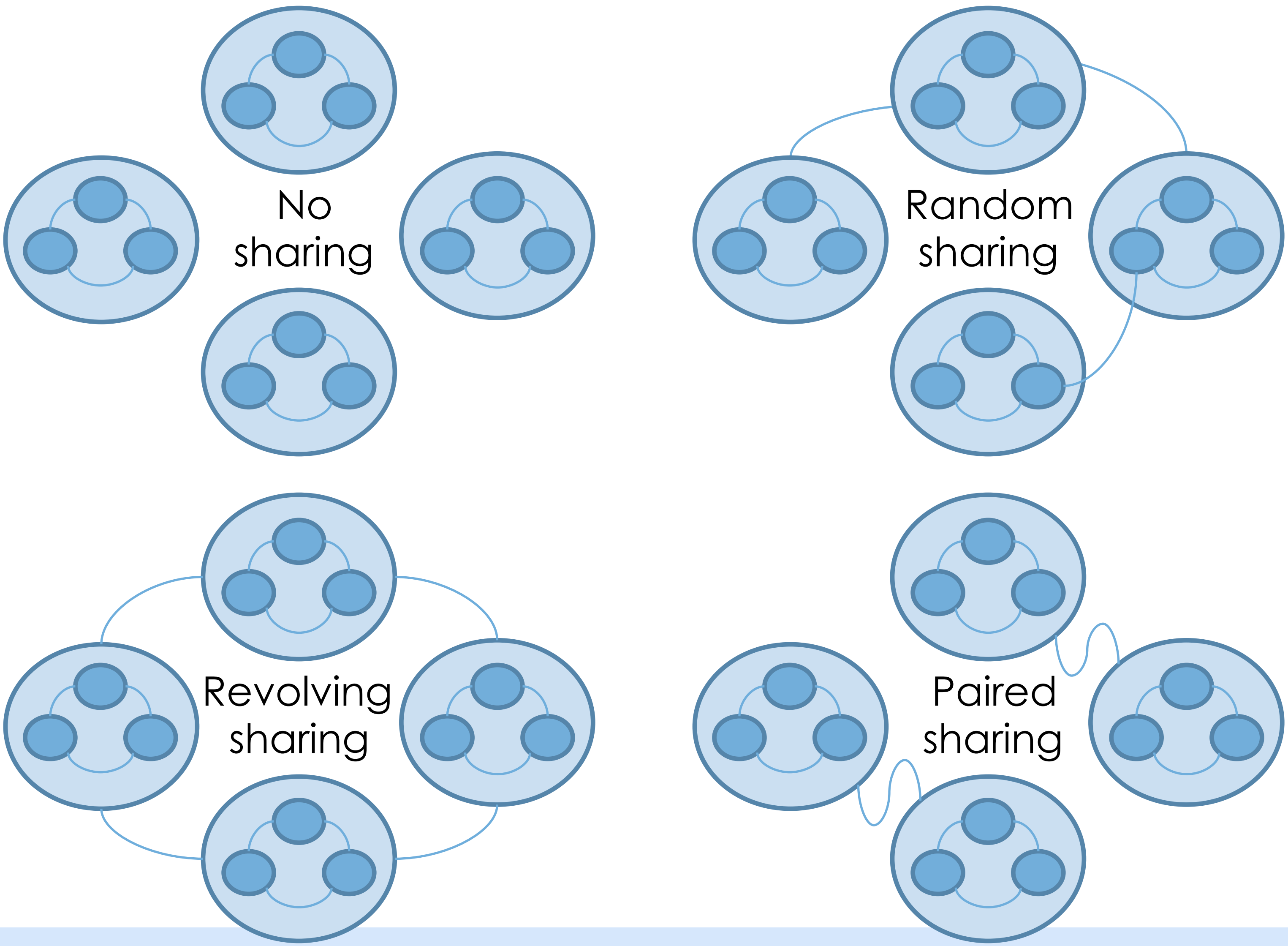
We can assign patients strategically in order to minimize the potential for transmission

- Assign all patients in a nurse cohort to the same physician

Effect: Slows the rate of transmission and limits its extent

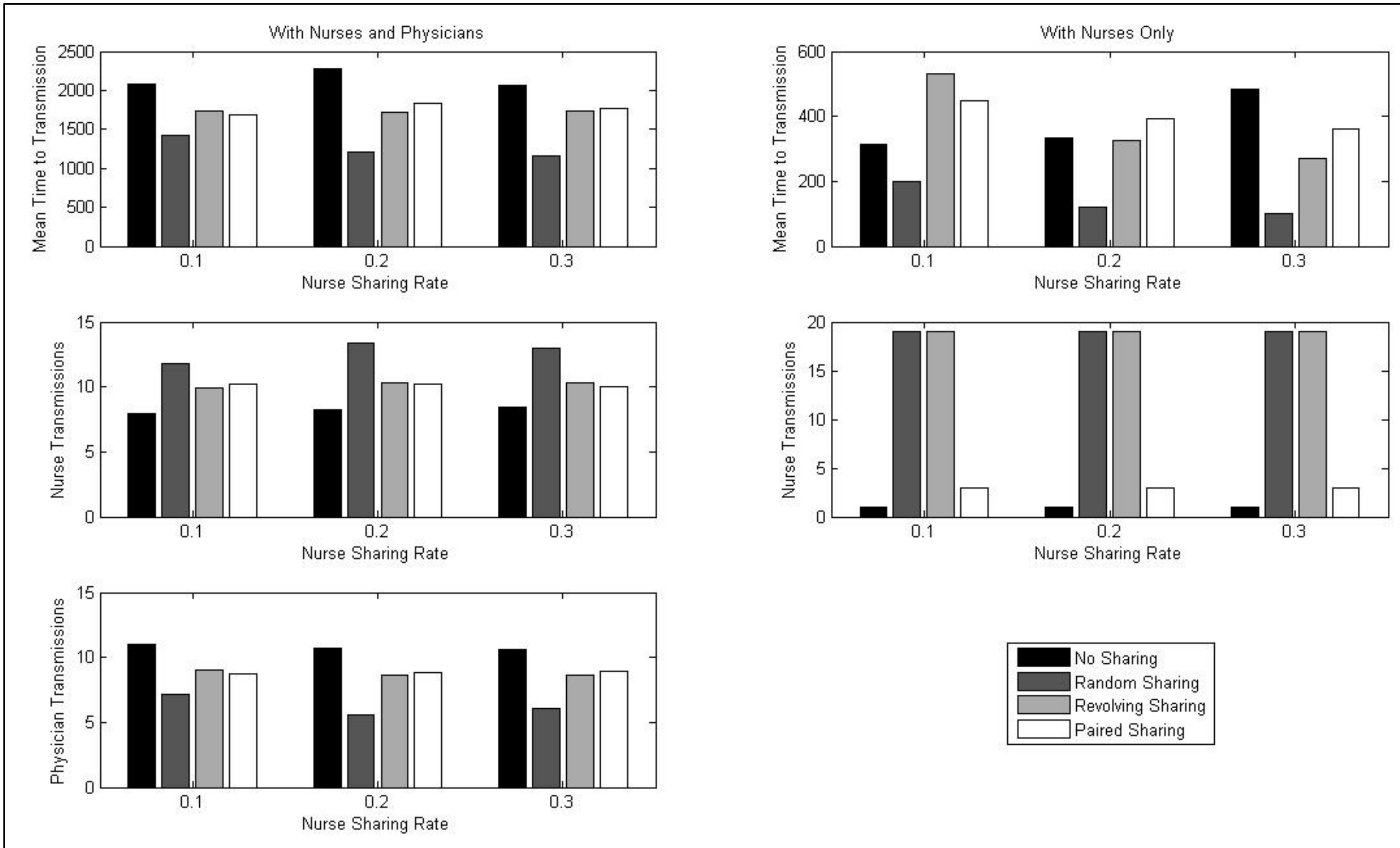


Patient Sharing



How does patient sharing affect transmission?

No sharing ≥ Revolving, paired (structured) sharing ≥ Random sharing
Physicians equalize effects of structured nurse sharing on transmission



HCW-to-HCW Transmission

Minimizing the density of the nurse and physician networks is needed to minimize transmission, but there is a higher risk for HCW-to-HCW transmission with more HCWs

Is there an optimal number of HCWs that minimizes transmission and balances the objective for a sparse patient network and minimal HCW-to-HCW transmission?

Conceptual Model

Each time step, we allow every pair of HCWs to interact at most one time

HCWs interact with equal probability, regardless of type, which is equivalent to a complete network with equally weighted links

Parameter	Definition
n	Number of patients
m	Number of healthcare workers
m_u , m_c	Number of uninfected and infected healthcare workers
c_m	Maximum number of relevant contacts, given m_U and m_C
p_c	Relevant contact probability
X	Random variable for the number of relevant contacts
p_t	Healthcare worker transmission probability
Y	Random variable for the number of HCW transmissions

Relevant Contacts

Relevant contacts are those between infected and susceptible individuals (i.e., contacts during which transmission can occur)

The maximum number of relevant contacts is given by $c_m = m_c \cdot m_u$

The probability of an adequate contact is the ratio of the maximum number of adequate contacts to the maximum number of HCW-to-HCW contacts

$$p_c = c_m \Big/ \binom{m}{2}$$

The number of relevant contacts is given by $X \sim \text{binomial}(c_m, p_c)$

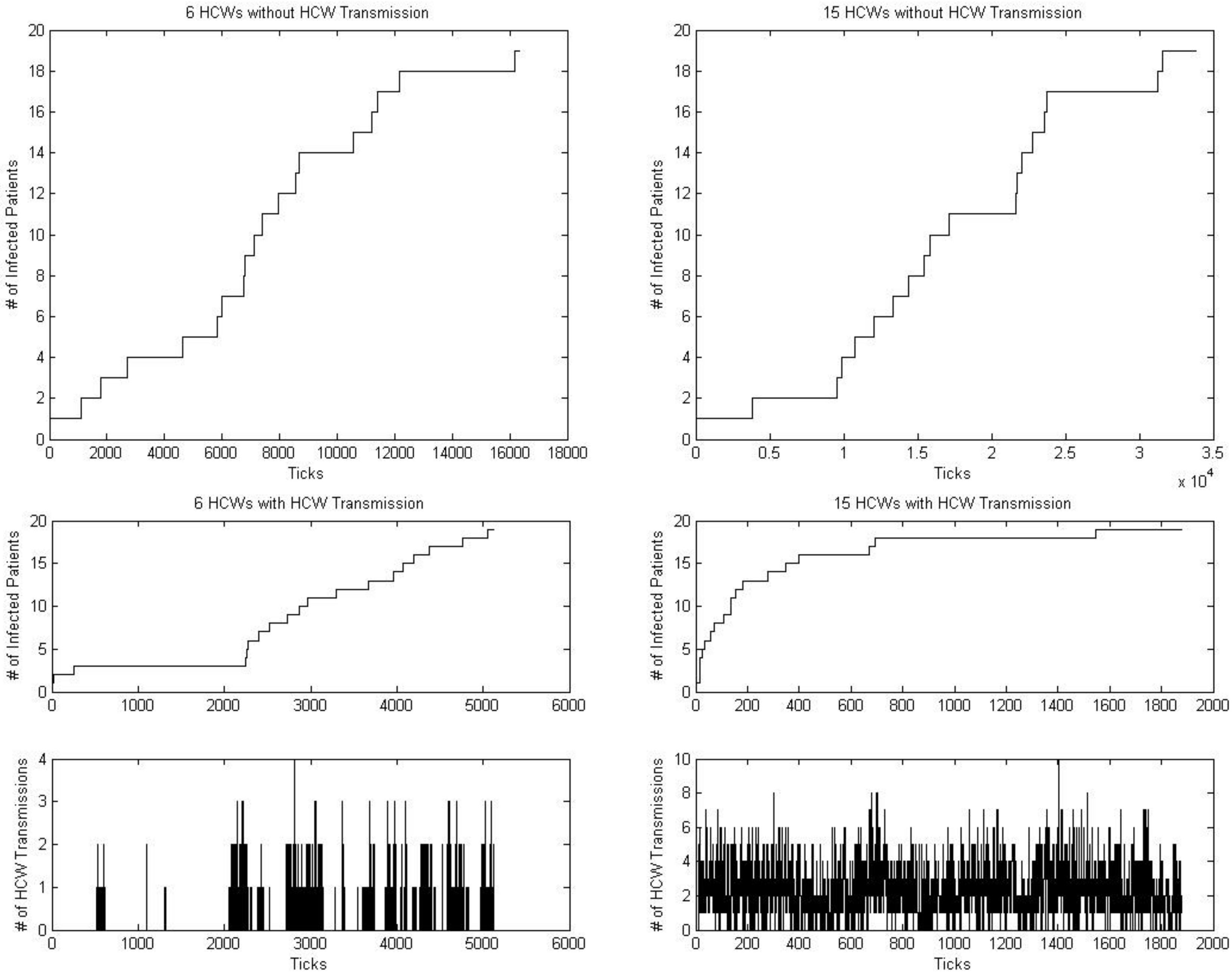
$$P(X = x) = \binom{c_m}{x} p_c^{\,x} (1 - p_c)^{c_m - x} \quad \text{for } x = 0, 1, \ldots, c_m$$

HCW-to-HCW Transmissions

Based on the number of relevant contacts, we can then model the number of HCW-to-HCW transmission as Y ~ binomial(X, p_t)

$$P(Y = y) = \binom{x}{y} p_t^{\,y} (1 - p_t)^{x-y} \quad \text{for } y = 0, 1, \ldots, x$$

Transmission Dynamics Comparison with and without HCW-to-HCW Transmission

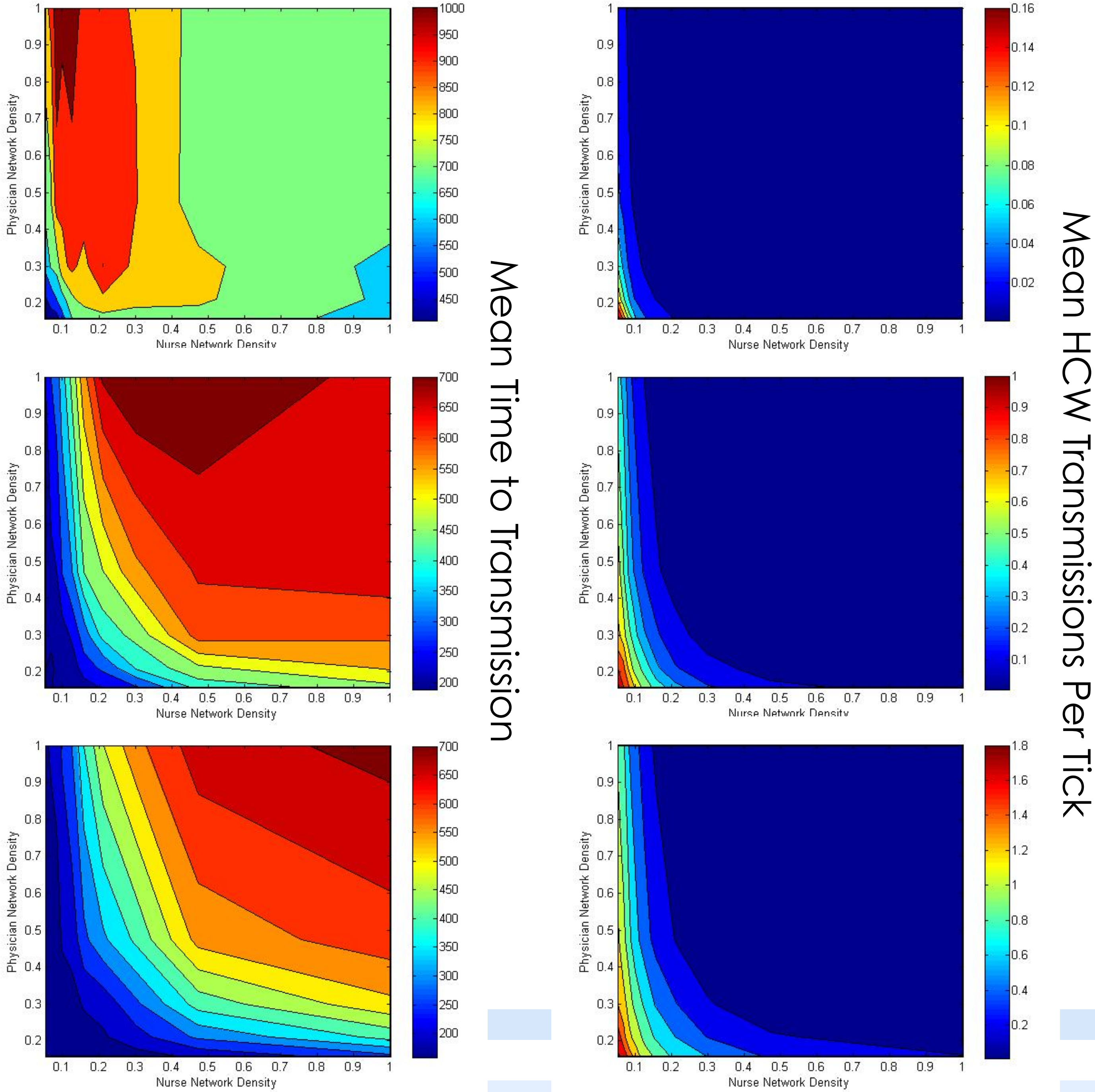


HCW-to-HCW Transmission Results

$p_t = 0.01$

$p_t = 0.05$

$p_t = 0.1$



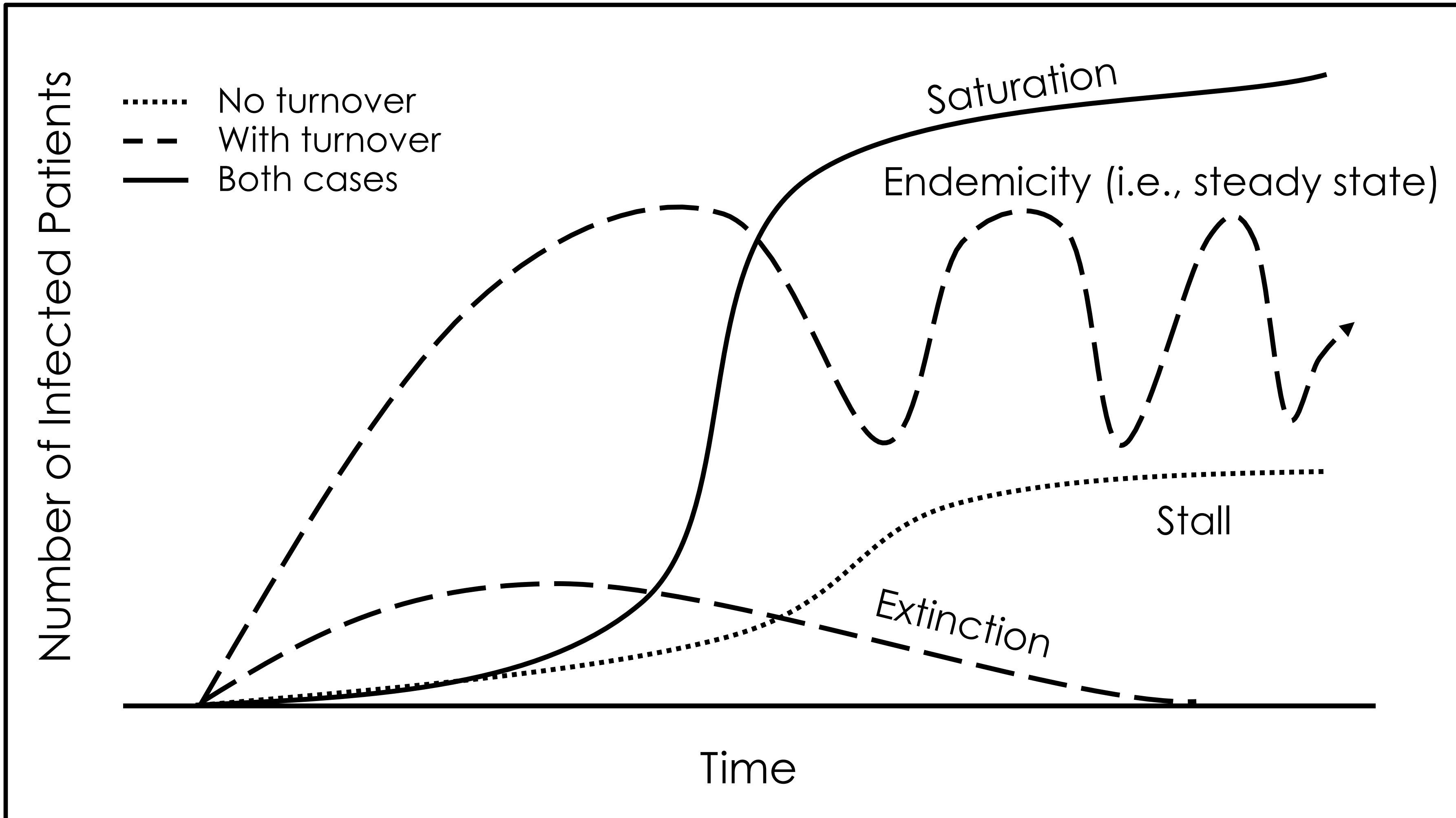
Patient Turnover

Patient turnover can change the colonization pressure in a hospital unit by shifting the balance between infected and susceptible patients

Patient turnover is implemented in the network model using two parameters

- Turnover rate {0,1}: Defines the rate (per tick) that patients are replaced in the network
  - Low (0.01) and high (0.1) turnover rates
- Admission prevalence {0,1}: Defines the probability that a new patient is infected
  - Nominal (0.1) and high (0.5) admission prevalence

Transmission Dynamics with Patient Turnover



Additional Experiments

Goal: Demonstrate how patient turnover changes transmission dynamics

Compare transmission dynamics with patient turnover to previous experiments

- Network density
- Patient sharing
- HCW-to-HCW transmission

All experiments were run until one of the following terminal conditions was met

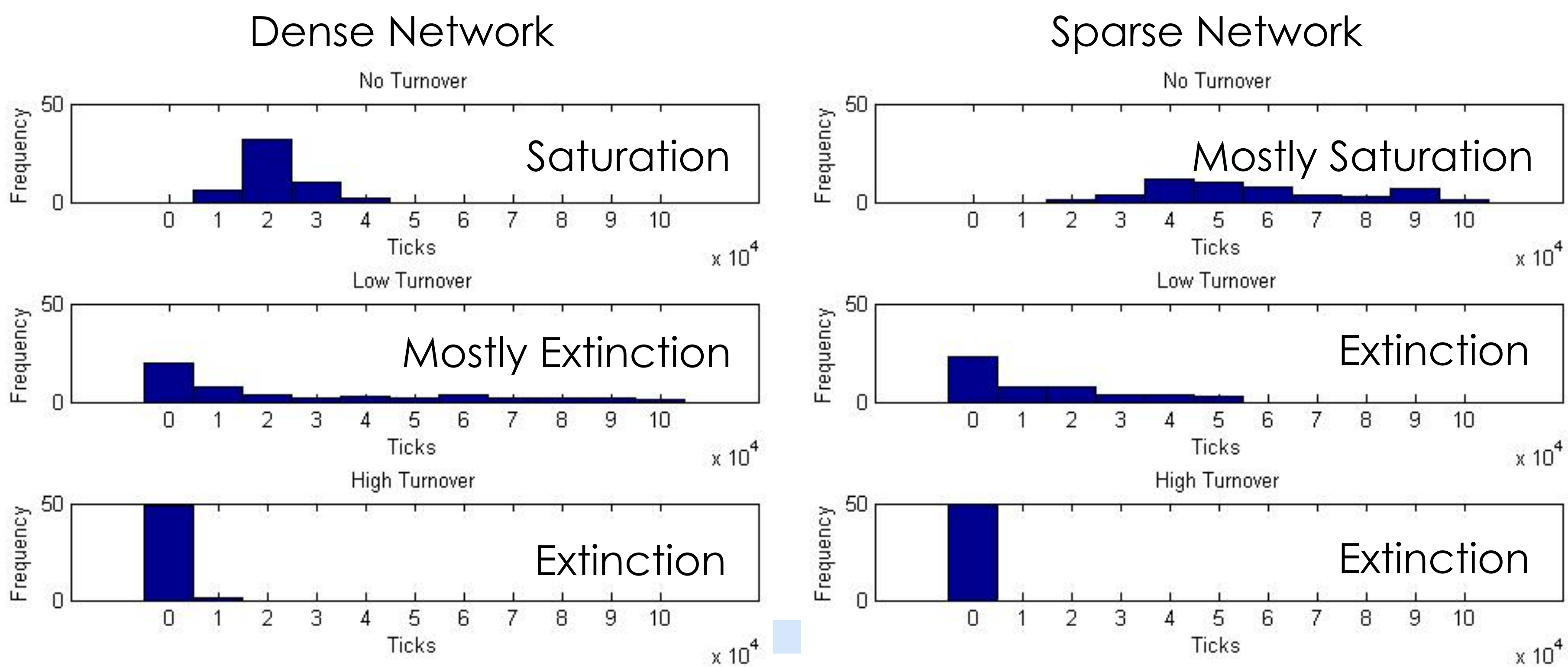
- No more infected patients in the unit (i.e., extinction)
- All patients in the unit become infected (i.e., saturation)
- 100,000 ticks (i.e., endemicity/steady state)

Network Density Comparison with Patient Turnover

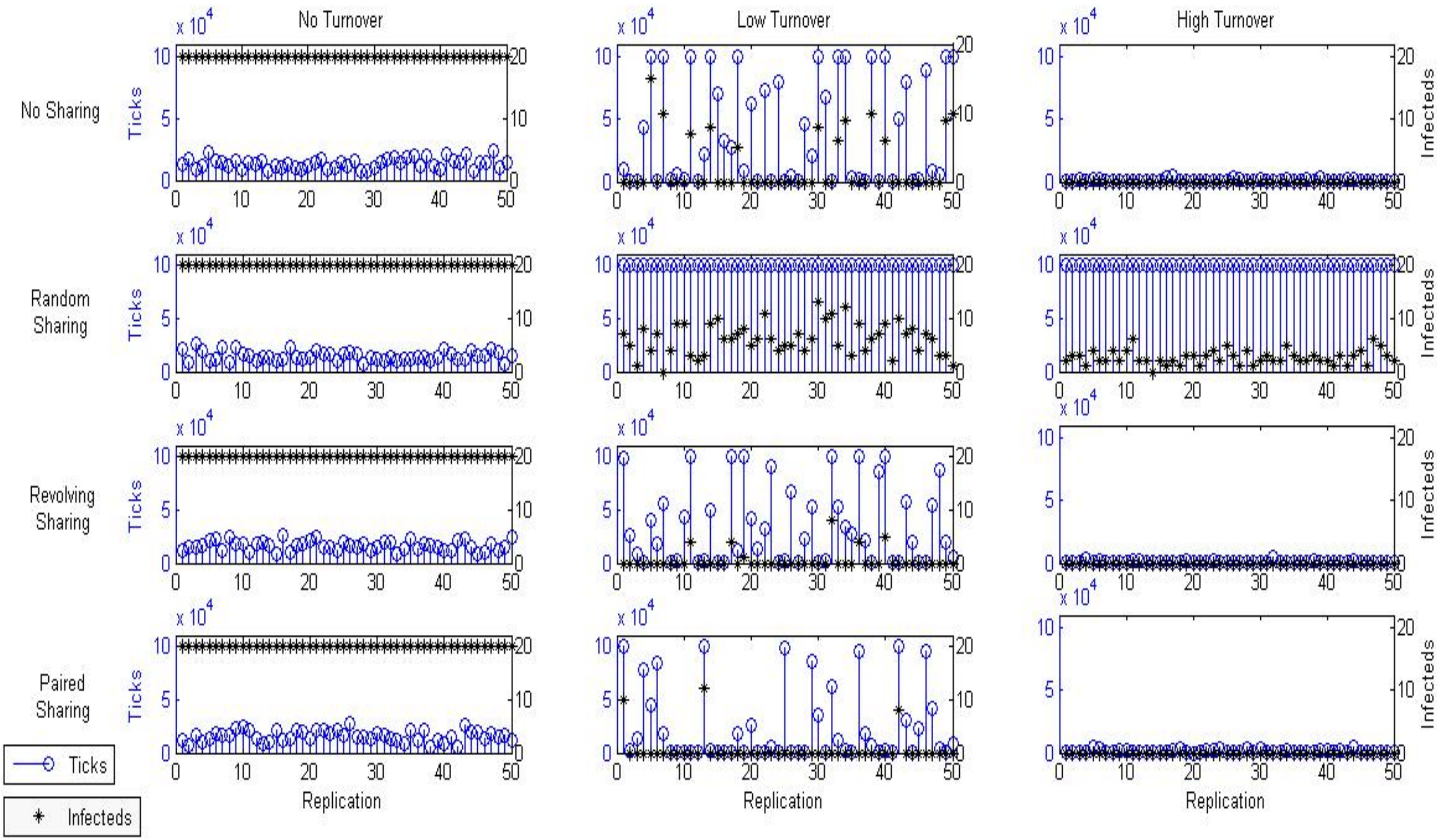
Transmission dynamics change from saturation to extinction as the patient turnover rate increases for both dense and sparse networks

- Transmission throughout sparse networks is slower in all cases
  - Lower saturation times, faster extinction times

These trends support the consensus that shorter lengths of stay for patients can decrease the likelihood they will acquire an infection during their stay



Patient Sharing with Turnover

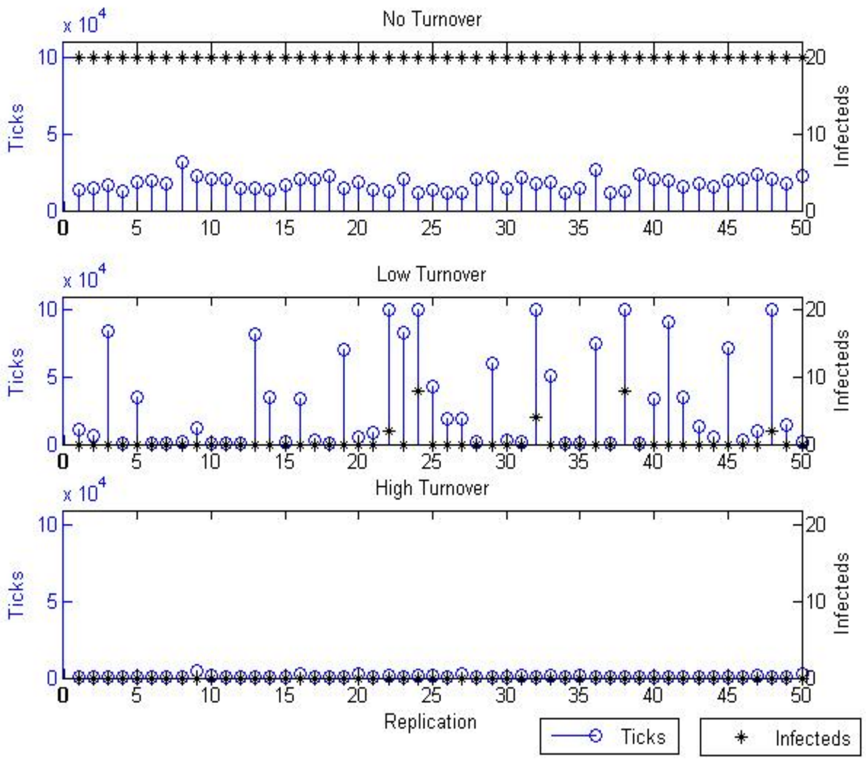


HCW-to-HCW Transmission with Patient Turnover

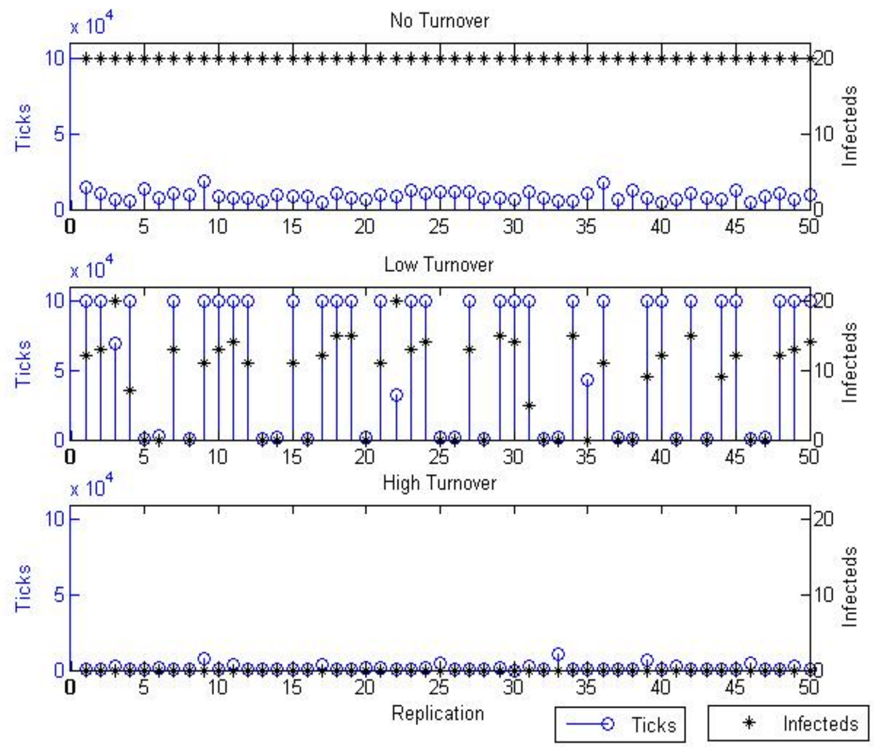
Similar trends for sparse and dense networks

- No turnover: Both networks saturate over all replications
- Low turnover: A mix of saturation and endemic outcomes
- High turnover: Clearly negates the effect of HCW-to-HCW transmission, leading to extinction very quickly

Dense Network



Sparse Network



High Admission Prevalence

Network Density Case	% of Cases (50 replications)		
	Extinction	Endemicity	Saturation
Dense with low turnover	8%	50%	42%
Dense with high turnover	8%	90%	2%
Sparse with low turnover	6%	86%	8%
Sparse with high turnover	0%	98%	2%

Sharing Configuration	Cases	% of Cases (50 replications)		
		Extinction	Endemicity	Saturation
None	No/Low/high turnover	0%/0%/12%	0%/38%/86%	100%/62%/2%
Random	No/Low/high turnover	0%/0%/0%	0%/50%/100%	100%/50%/0%
Revolving	No/Low/high turnover	0%/6%/2%	0%/60%/98%	100%/34%/0%
Shared	No/Low/high turnover	0%/6%/6%	0%/64%/90%	100%/30%/4%

HCW-to-HCW Transmission Case	% of Cases (50 replications)		
	Extinction	Endemicity	Saturation
Dense with low turnover	10%	52%	38%
Dense with high turnover	6%	88%	6%
Sparse with low turnover	6%	8%	86%
Sparse with high turnover	8%	86%	6%

Conclusions

- Network structure provides a new perspective on transmission dynamics in a closed population
  - Minimizing transmission requires maintaining adequate densities and preventing overlap of nurse and physician networks
  - Patient sharing should be kept to a minimum and, when done, should be done in a structured manner
- HCW-to-HCW transmission is a potentially critical factor for patient-to-patient transmission in a hospital, and becomes the dominating factor when many HCWs are caring for patients
- Patient turnover can reduce the risk of transmission in a hospital unit and lead many outbreaks to extinction
  - High admission prevalence can lead to endemic or saturated hospital outcomes

Questions and Comments

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