Evaluating Architectural Changes to Alter Pathogen Dynamics in a Dialysis Unit

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Introduction

Spread of MRSA among dialysis patients

- Dialysis patients are susceptible to hospital acquired infections (HAI)
  - Visit dialysis center 3 times per week
  - Immunocompromised
  - Long-term vascular access

Office of Disease Prevention and Health Promotion at health.gov, “Overview: Health care-associated infections,” https://health.gov/hcq/prevent-hai.asp

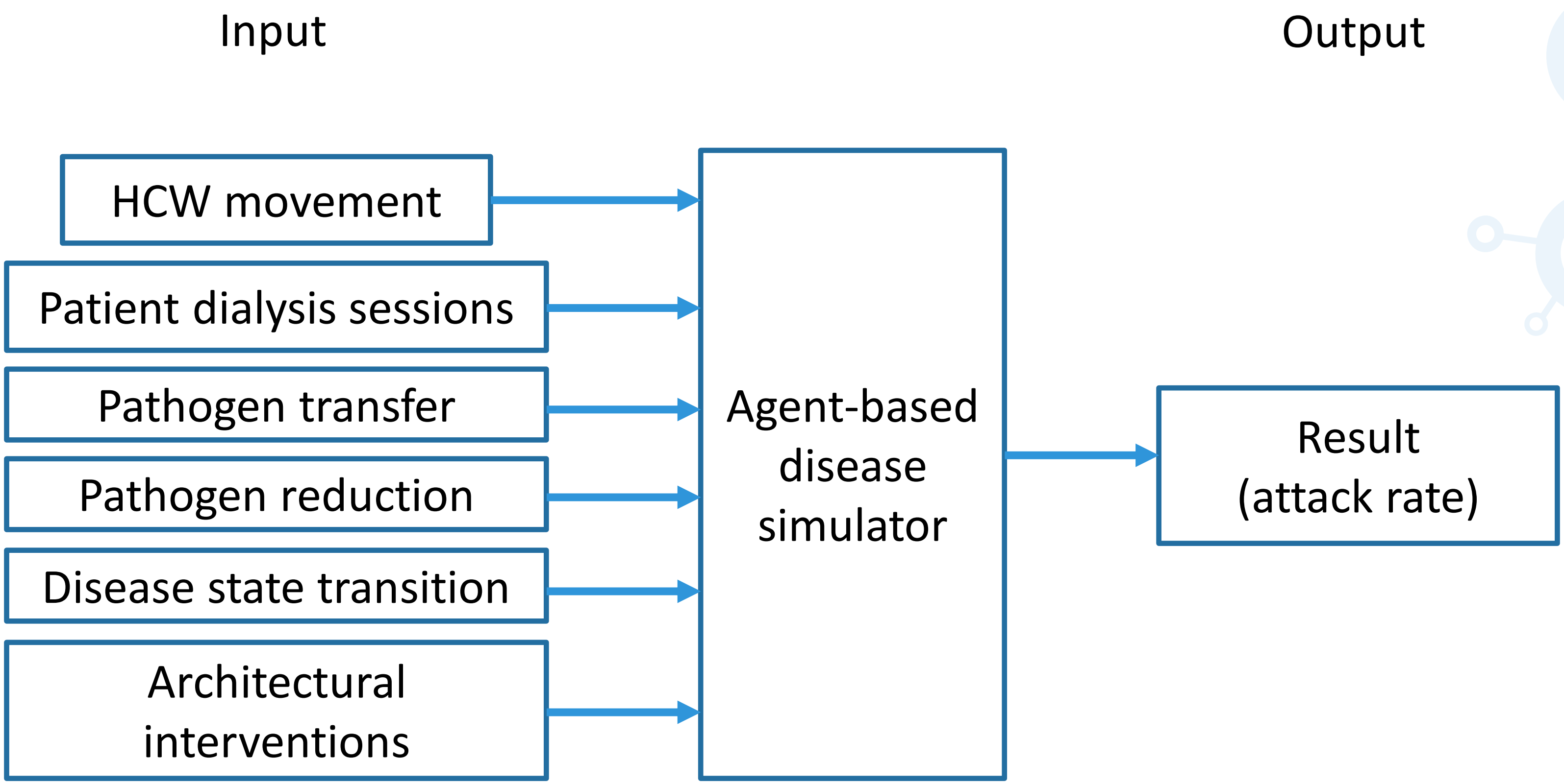
Introduction

Spread of MRSA among dialysis patients

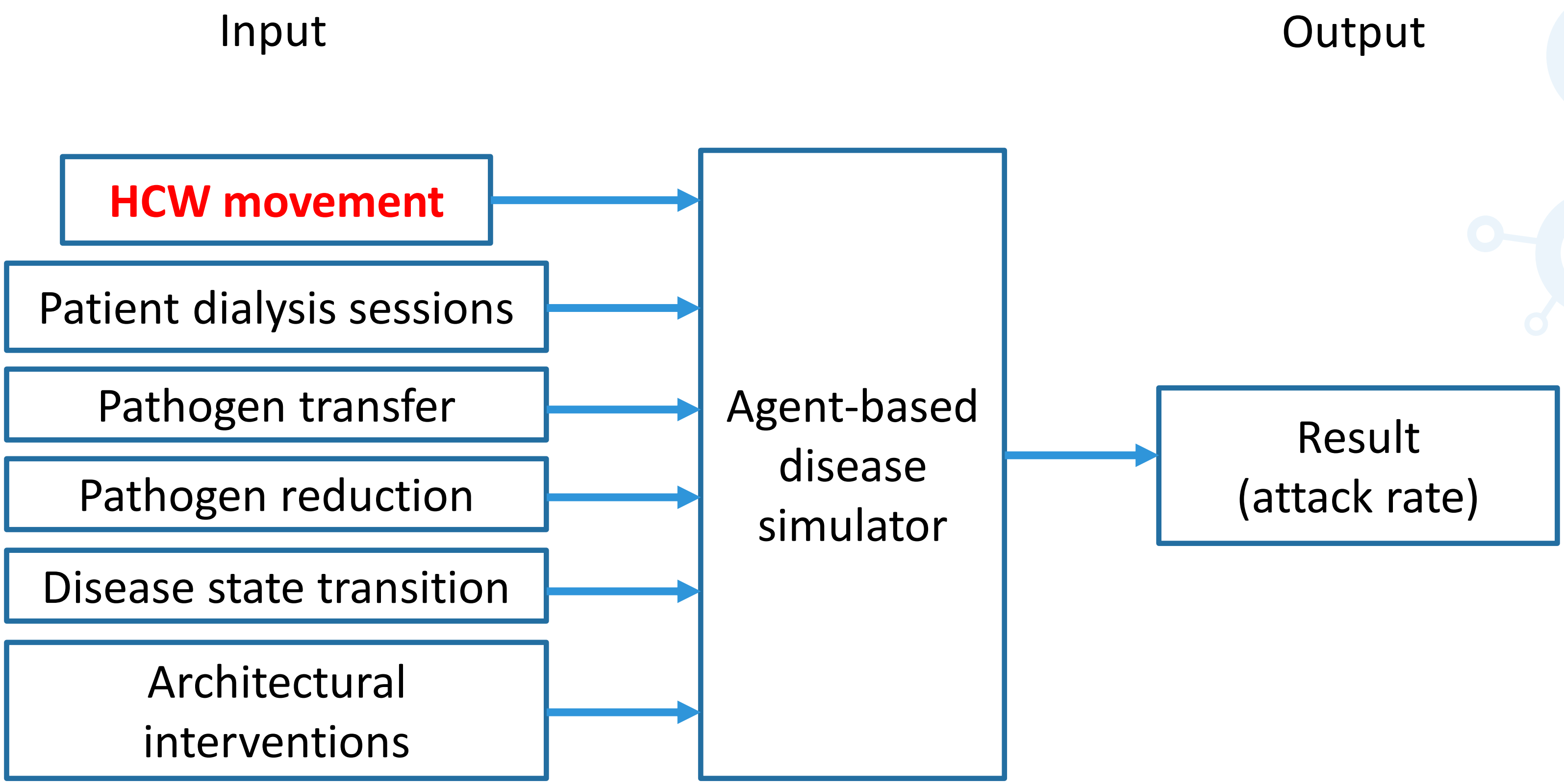
- MRSA is common among dialysis patients
- Interventions suggested to reduce the spread of MRSA
  – Increase HCW hand hygiene
  – Clean environments more frequently
- Any other changes to further reduce MRSA?
- Would architectural changes help?

J. Schieszer, “Invasive MRSA hits dialysis patients,” Renal and UrologyNews, December 2007
Centers for Disease Control and Prevention (CDC), “Methicillin-resistant Staphylococcus aureus (MRSA): General information,” https://www.cdc.gov/mrsa/community/index.html

Overview


Input
Output
HCW movement
Patient dialysis sessions
Pathogen transfer
Pathogen reduction
Disease state transition
Architectural interventions
Agent-based disease simulator
Result (attack rate)

Overview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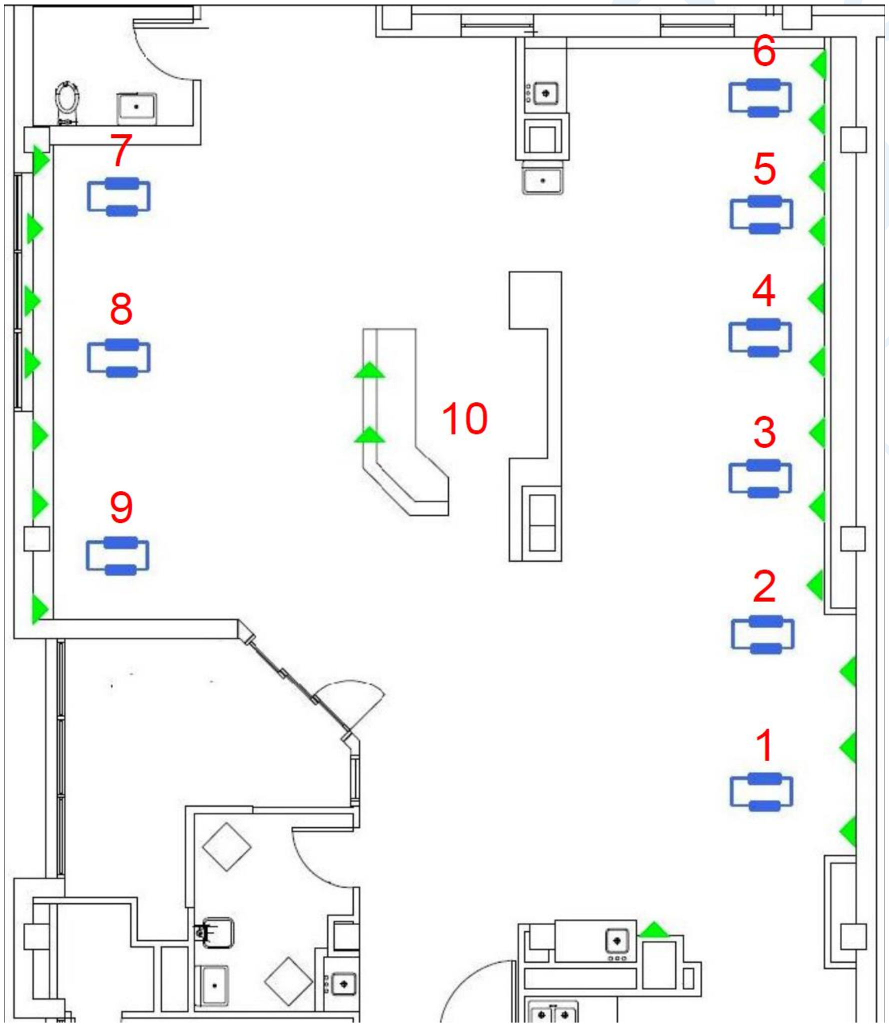
HCW movement and interaction

Dialysis unit instrumentation (2013 Fall)

- The University of Iowa Hospitals and Clinics (UIHC), dialysis unit
- Beacons (▲)
- Badges distributed to HCWs
- Badges send signal (/ 8s)
- Beacons receive signal and record
  - Badge id
  - Time
  - Received signal strength index (RSSI)
- Result: (x, y) coordinates for HCWs in 8s time windows



T. Herman et al., "Wireless applications for hospital epidemiology," in 1st Association for Computing Machinery International Workshop on Medical-Grade Wireless Networks, New Orleans, LA, May18 2009, pp.45–50

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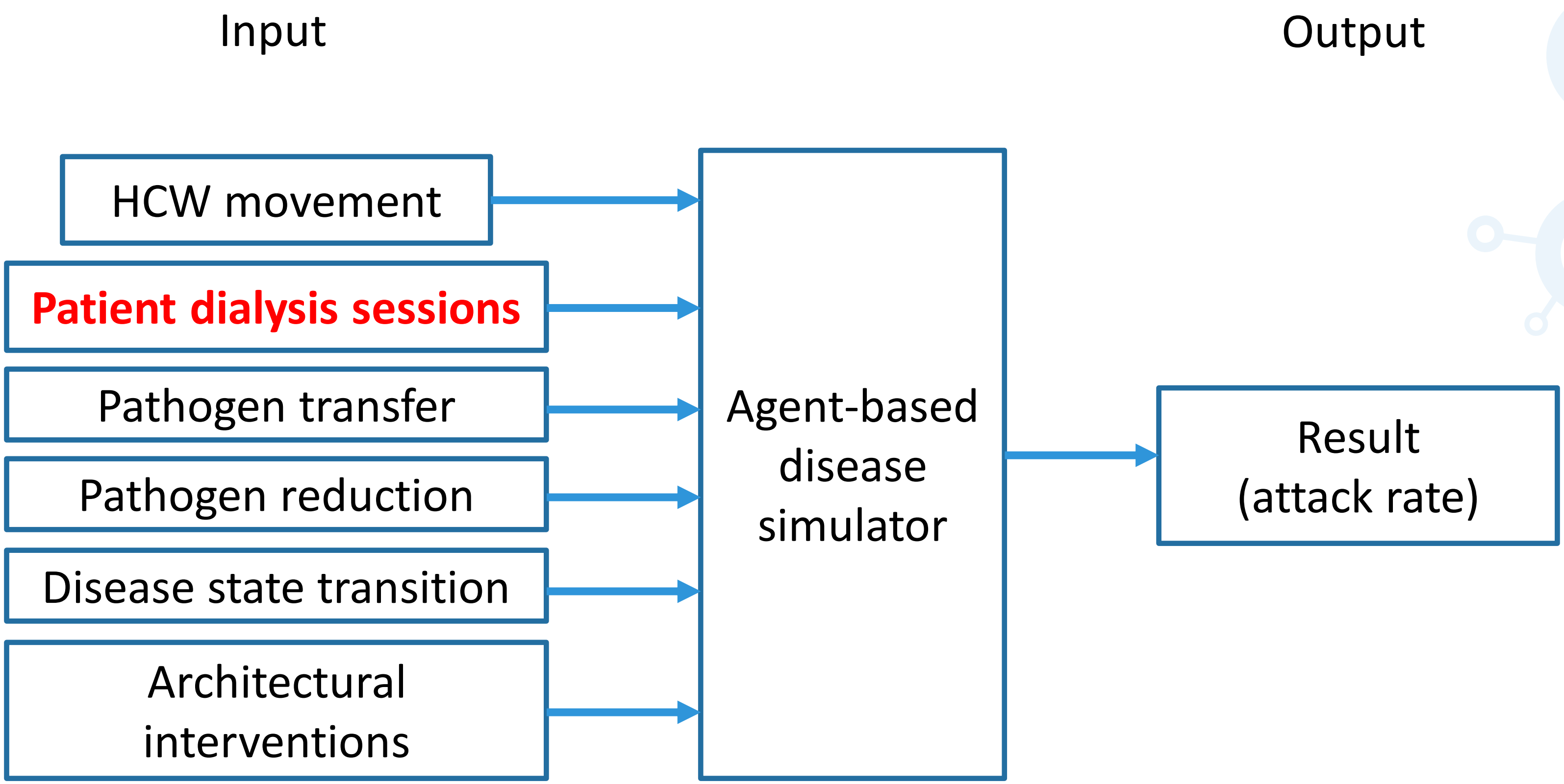
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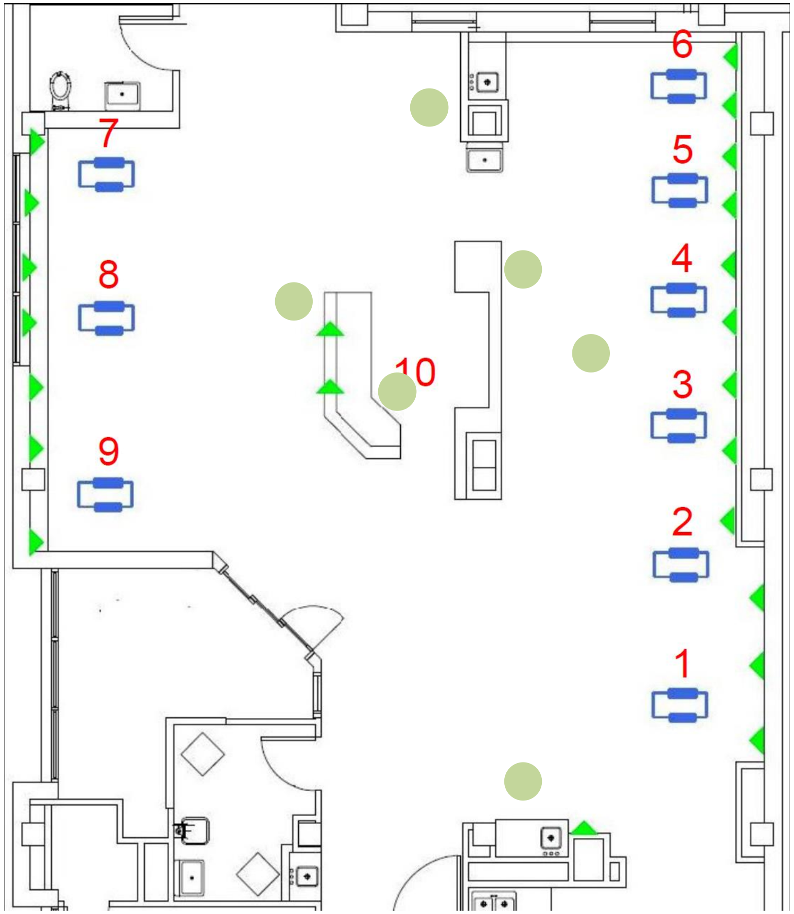
Impute patient dialysis sessions

No patient records



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Impute patient dialysis sessions

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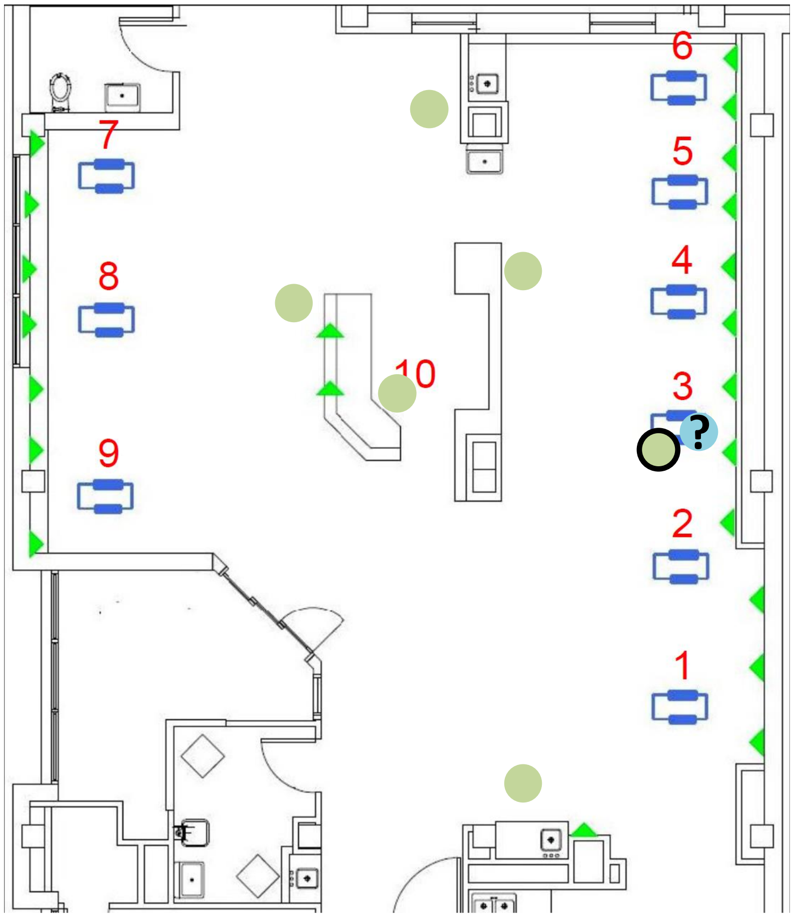

A HCW spends prolonged time at a chair

Impute patient dialysis sessions

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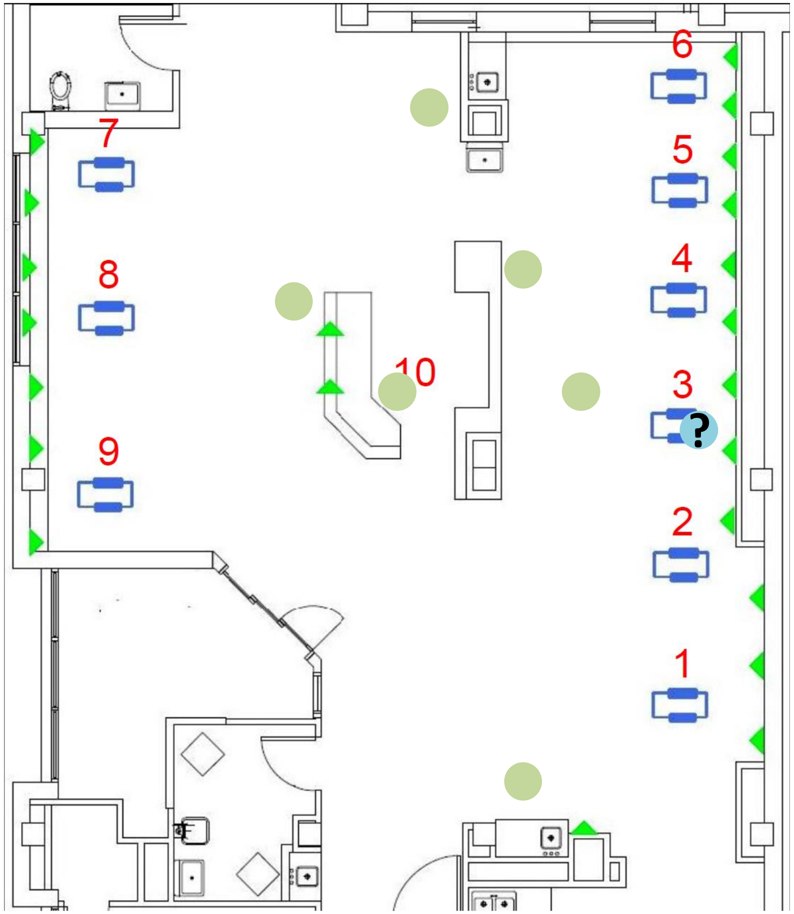
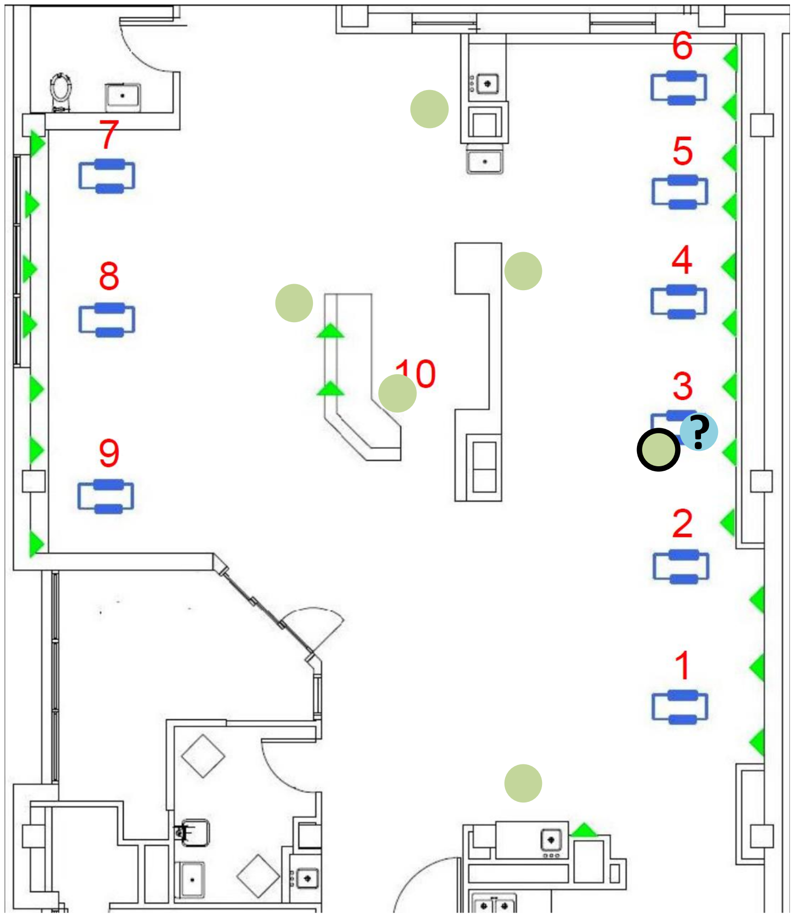


Patient gets a dialysis treatment for 3-4 hours

Impute patient dialysis sessions

No patient records

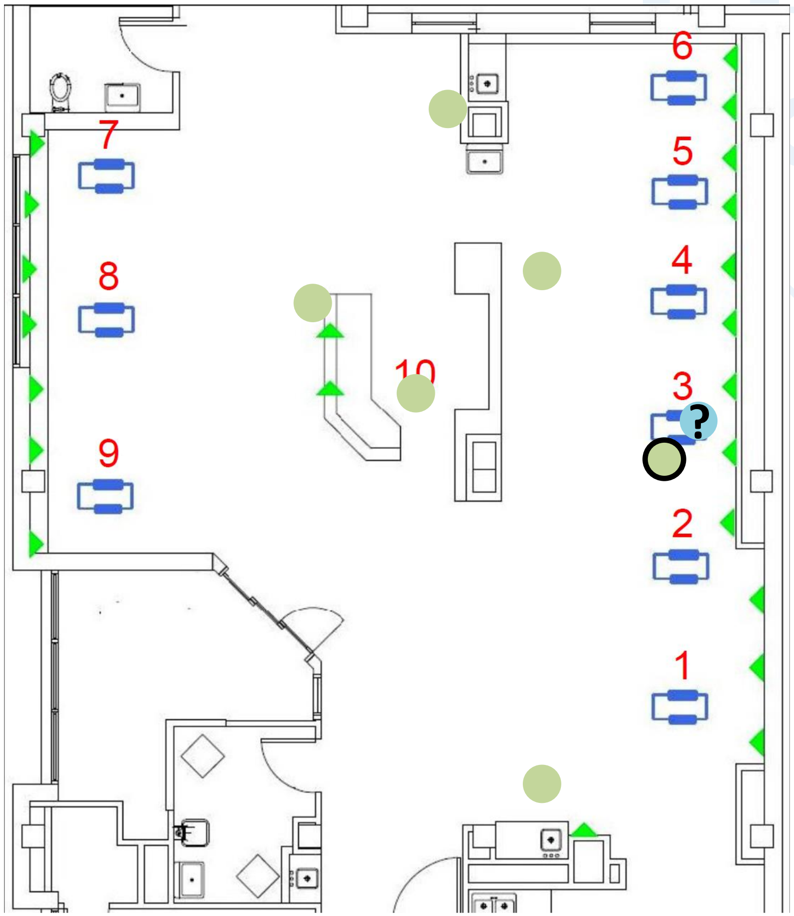


A HCW spends prolonged time at a chair

Impute patient dialysis sessions

Imputing dialysis session at chair 3

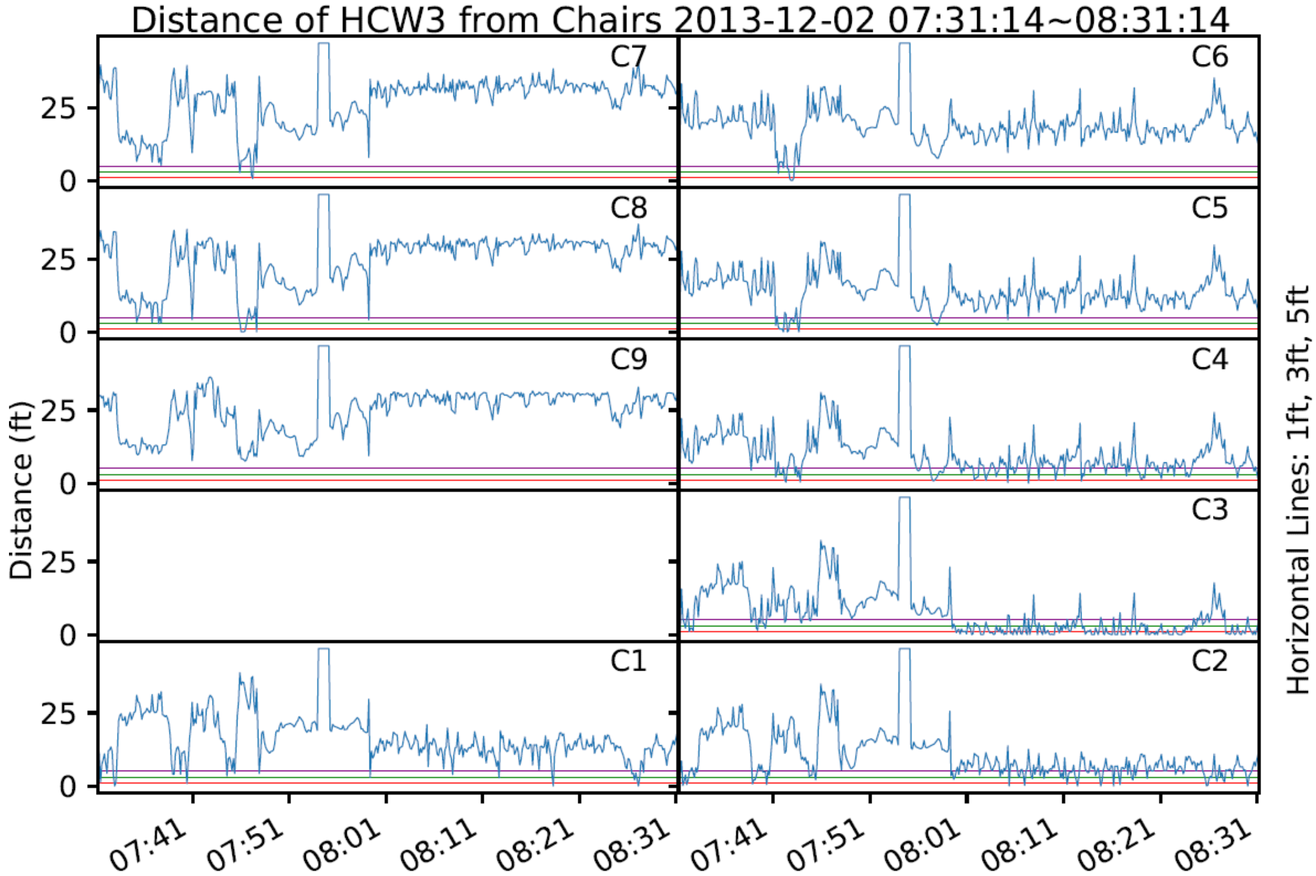
- Event: Extended interaction
- Detect events at chair 3
- Look for events that are 3-4 hours apart
  - Former event: Start of the dialysis session
  - Later event: End of the dialysis session



Impute patient dialysis sessions

Calculate distance of each HCW to chairs

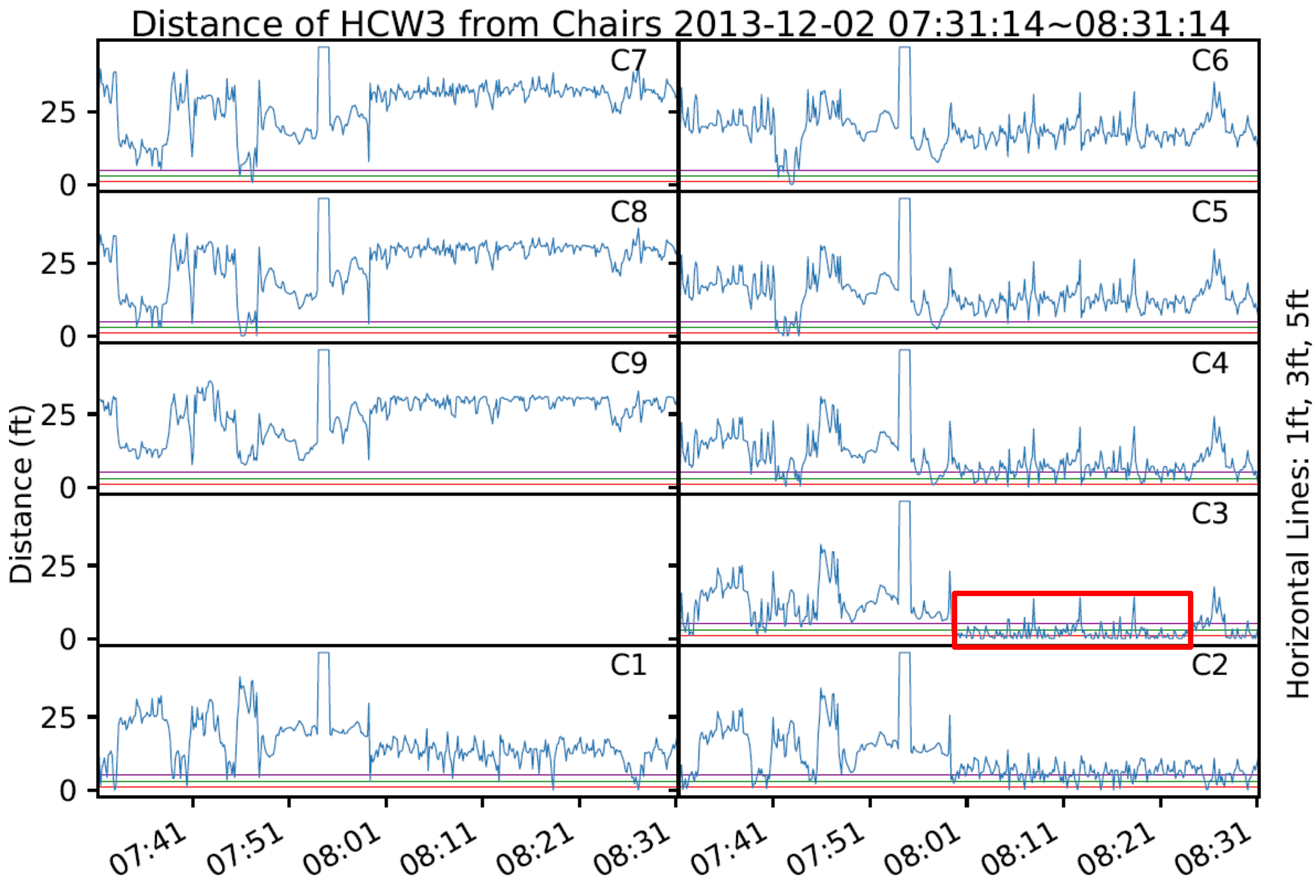
Event: Extended interaction



Impute patient dialysis sessions

HCW3 spends prolonged time at chair 3

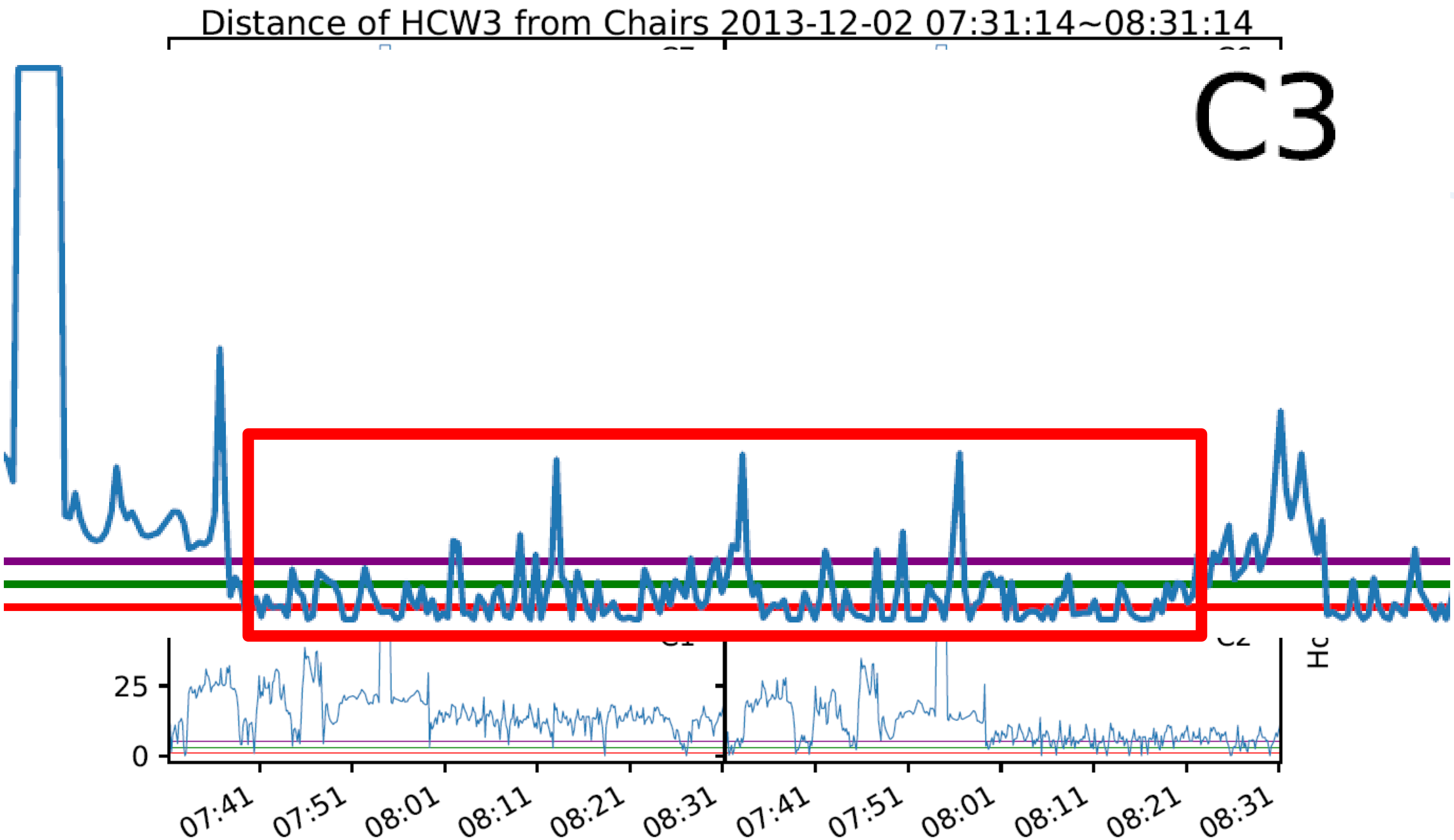
Event: Extended interaction



Impute patient dialysis sessions

HCW3 spends prolonged time at chair 3

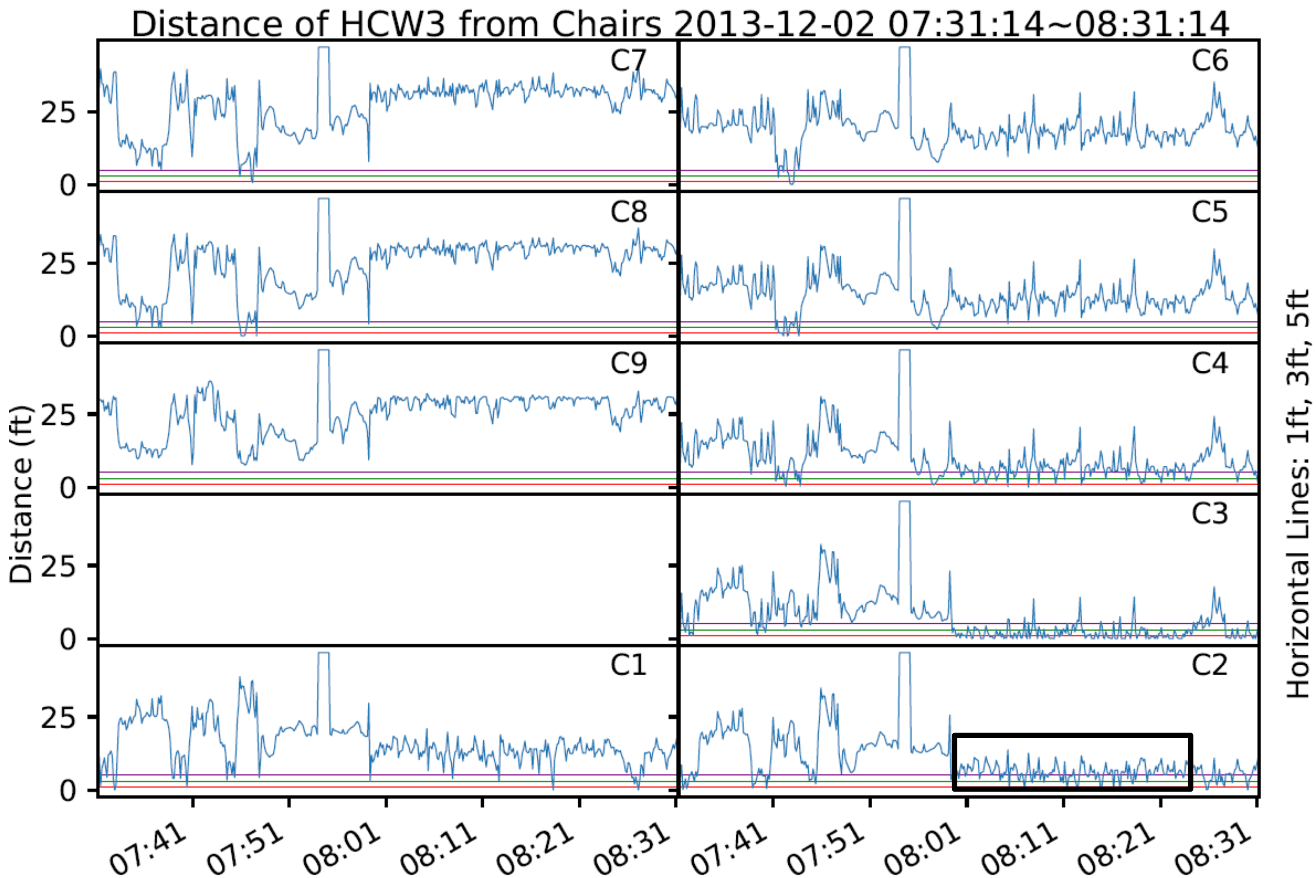
Event: Extended interaction



Impute patient dialysis sessions

Select next closest chair from chair 3

Event: Extended interaction



Impute patient dialysis sessions

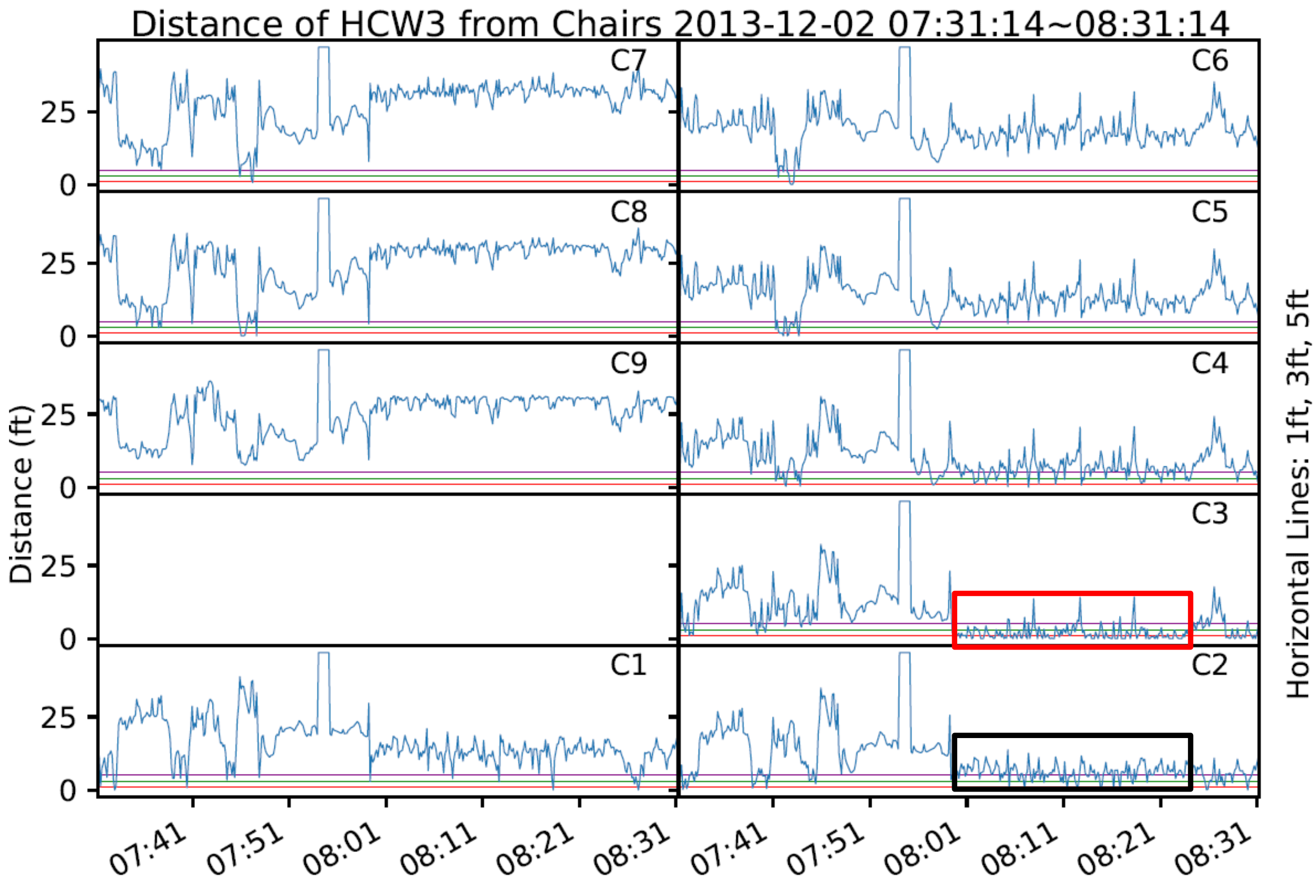
Select ne›

Event: Ext‹

Impute patient dialysis sessions

Manually select these sequences

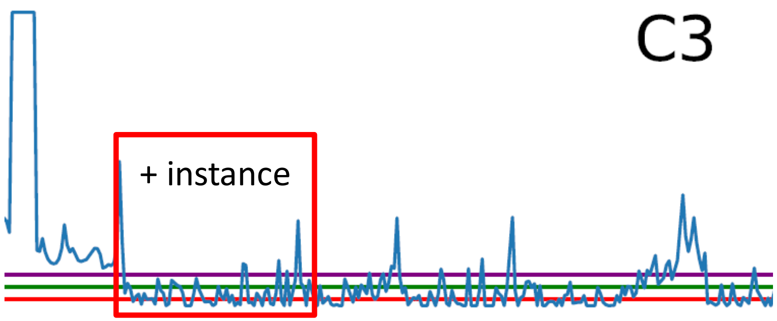
Event: Extended interaction



Impute patient dialysis sessions

Generate dataset

Event: Extended interaction



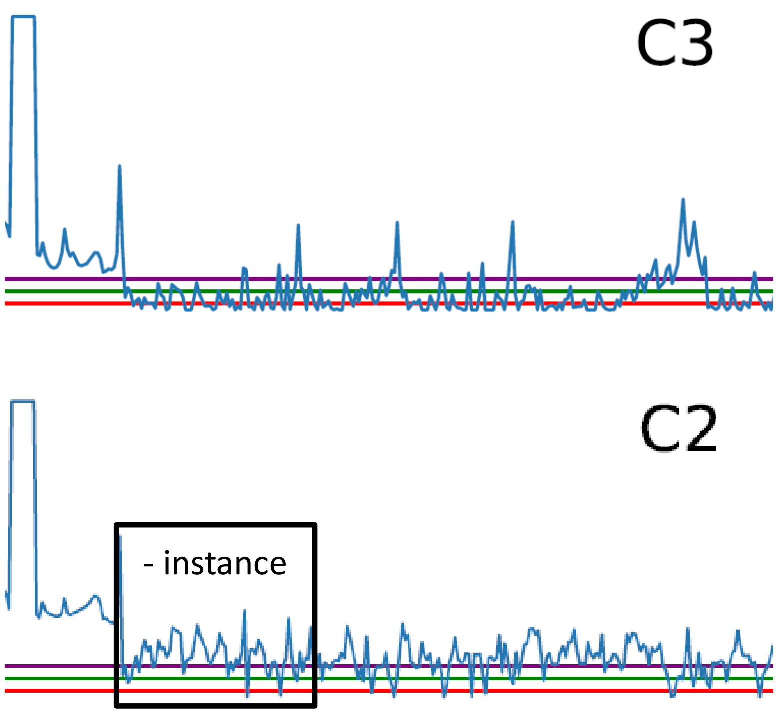
~ 2K positive instances

f_1	f_2	f_3	...	f_{55}	f_{56}	Label
3	4	1	...	5	3	True
4	1	3	...	3	4	True
1	3	.5	...	4	1	True
...	...	...	...	...	...	...

Impute patient dialysis sessions

Generate dataset, train a neural network model

Event: Extended interaction



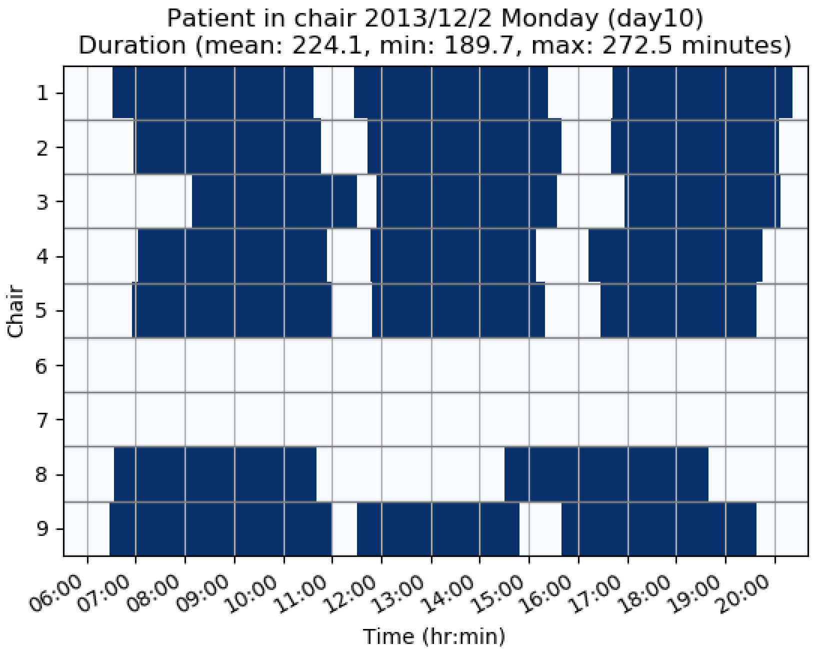
~ 2K positive instances
~ 4K negative instances

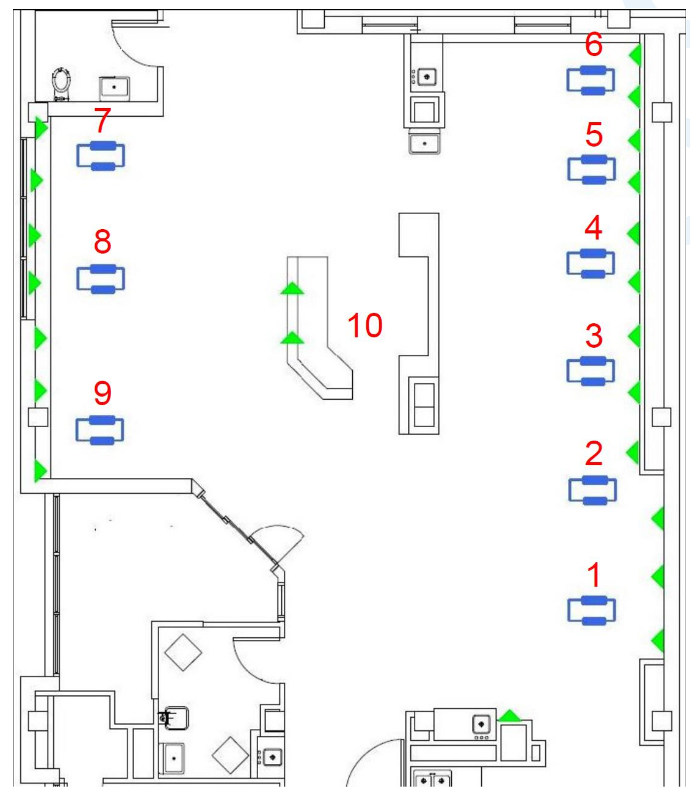
f_1	f_2	f_3	...	f_{55}	f_{56}	Label
3	4	1	...	5	3	True
4	1	3	...	3	4	True
1	3	.5	...	4	1	True
...	...	...	...	...	...	...
3	7	10	...	3	1	False
7	10	8	...	1	5	False
10	8	13	...	5	3	False

Impute patient dialysis sessions

Generate patient sessions

- Apply the classifier to all of our HCW/chair data
- Dialysis sessions predicted by the classifier looks like real dialysis sessions



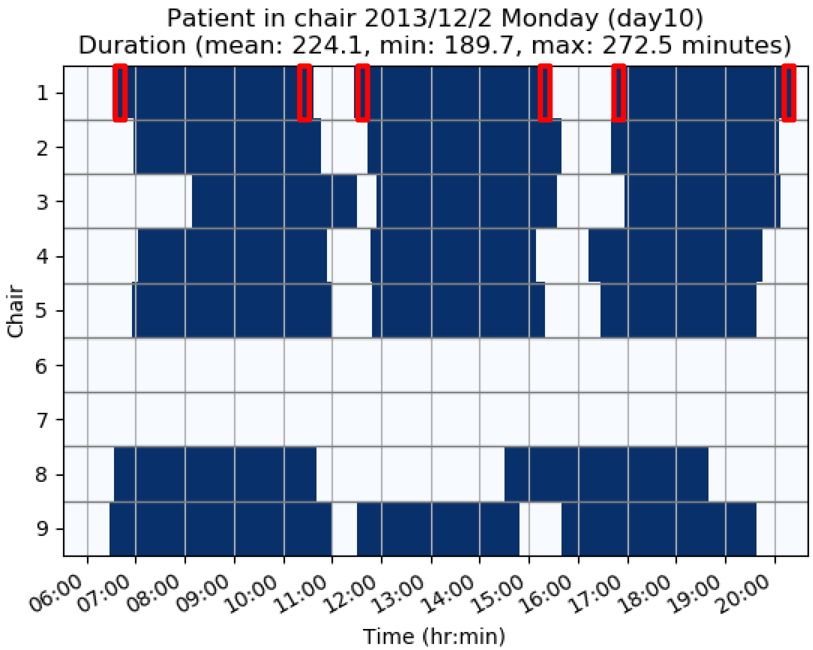


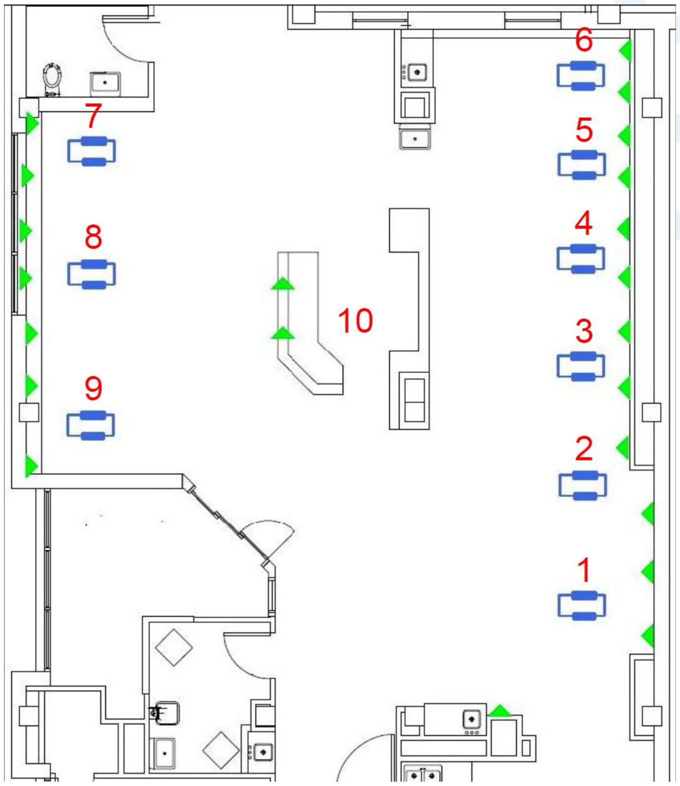
Rivara MB, Adams SV, Kuttykrishnan S, Kalantar-Zadeh K, Arah OA, Cheung AK, Katz R, Molnar MZ, Ravel V, Soohoo M, Streja E, Himmelfarb J, Mehrotra R. Extended-hours hemodialysis is associated with lower mortality risk in patients with end-stage renal disease. *Kidney Int*. 2016 Dec;90(6):1312-1320. doi: 10.1016/j.kint.2016.06.028. Epub 2016 Aug 20. PubMed PMID: 27555118; PubMed Central PMCID: PMC5123950.

Impute patient dialysis sessions

Generate patient sessions

- Apply the classifier to all of our HCW/chair data
- Dialysis sessions predicted by the classifier looks like real dialysis sessions (211 ± 27 mins)





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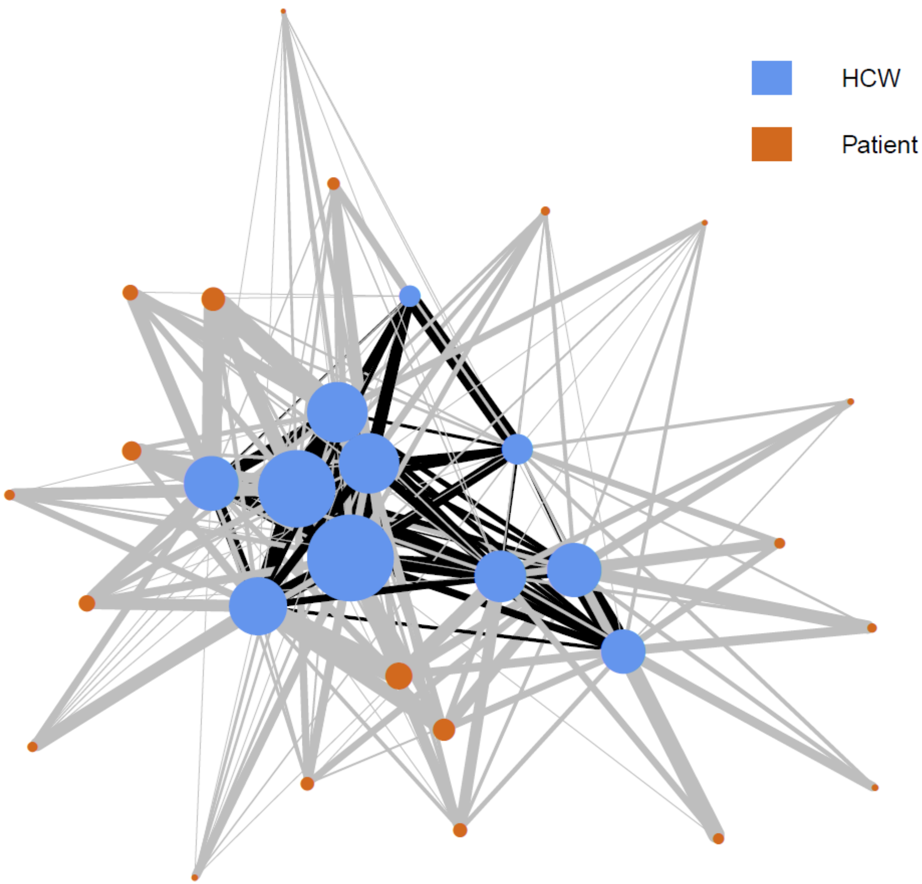
Impute patient dialysis sessions

Contact Network



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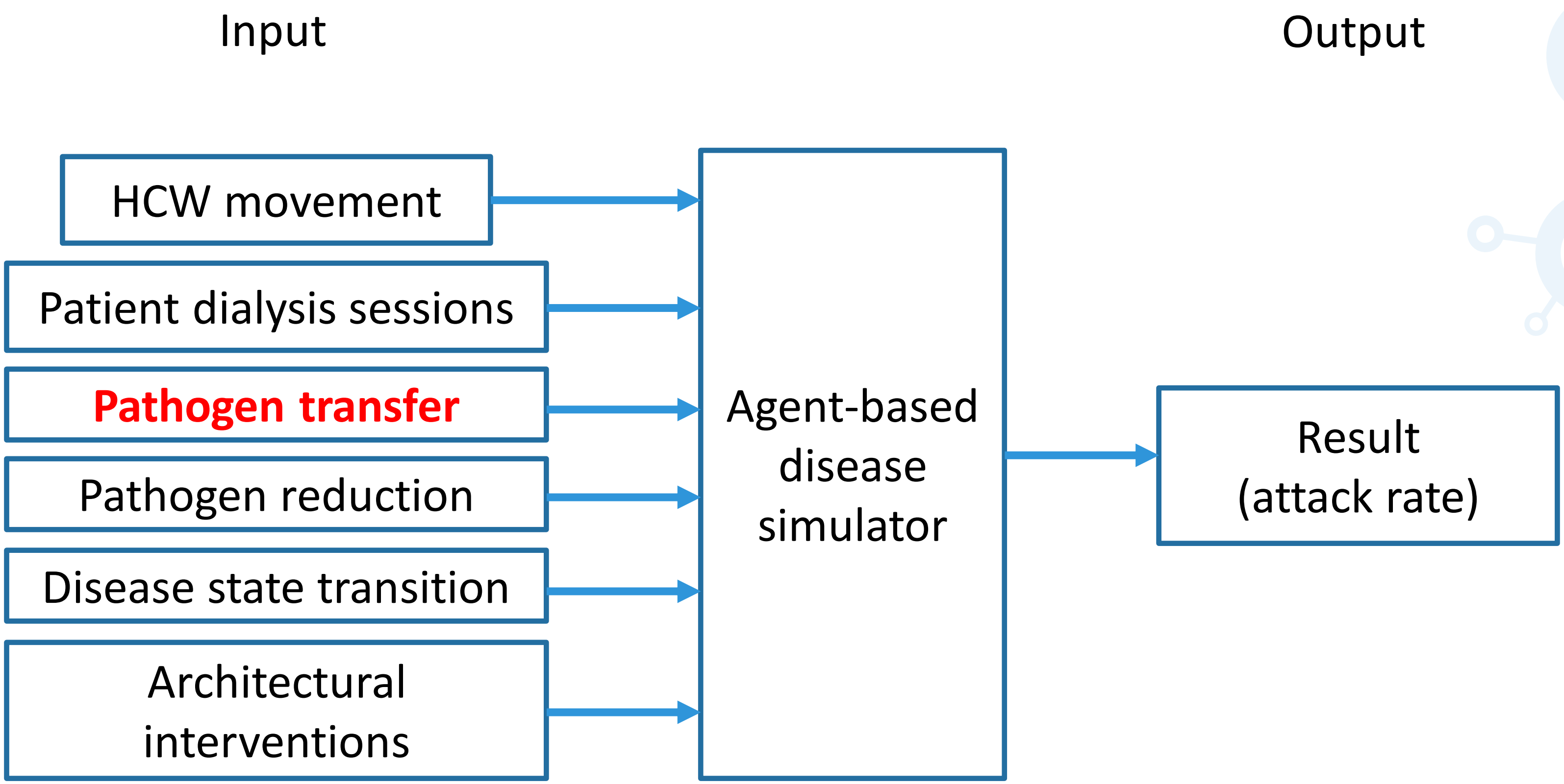
Overview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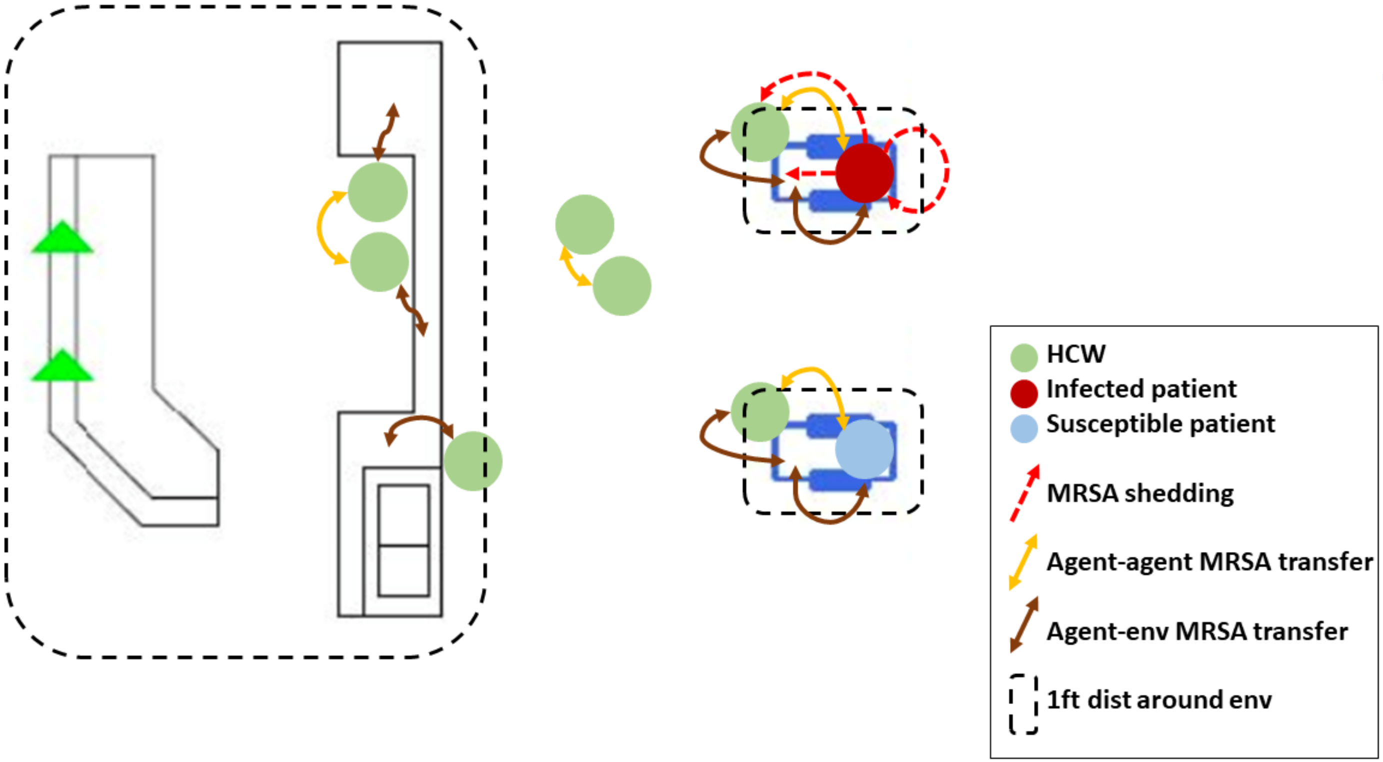
Simulating the spread of MRSA in the dialysis unit

Pathogen transfer

- Pathogen spreads uniformly over all the surfaces
- Contact between entities results in MRSA transfer



N. Plipat et al., "The dynamics of methicillin-resistant Staphylococcus aureus exposure in a hospital model and the potential for environmental intervention," BMC infectious diseases, vol.13, no.1, p.595, 2013

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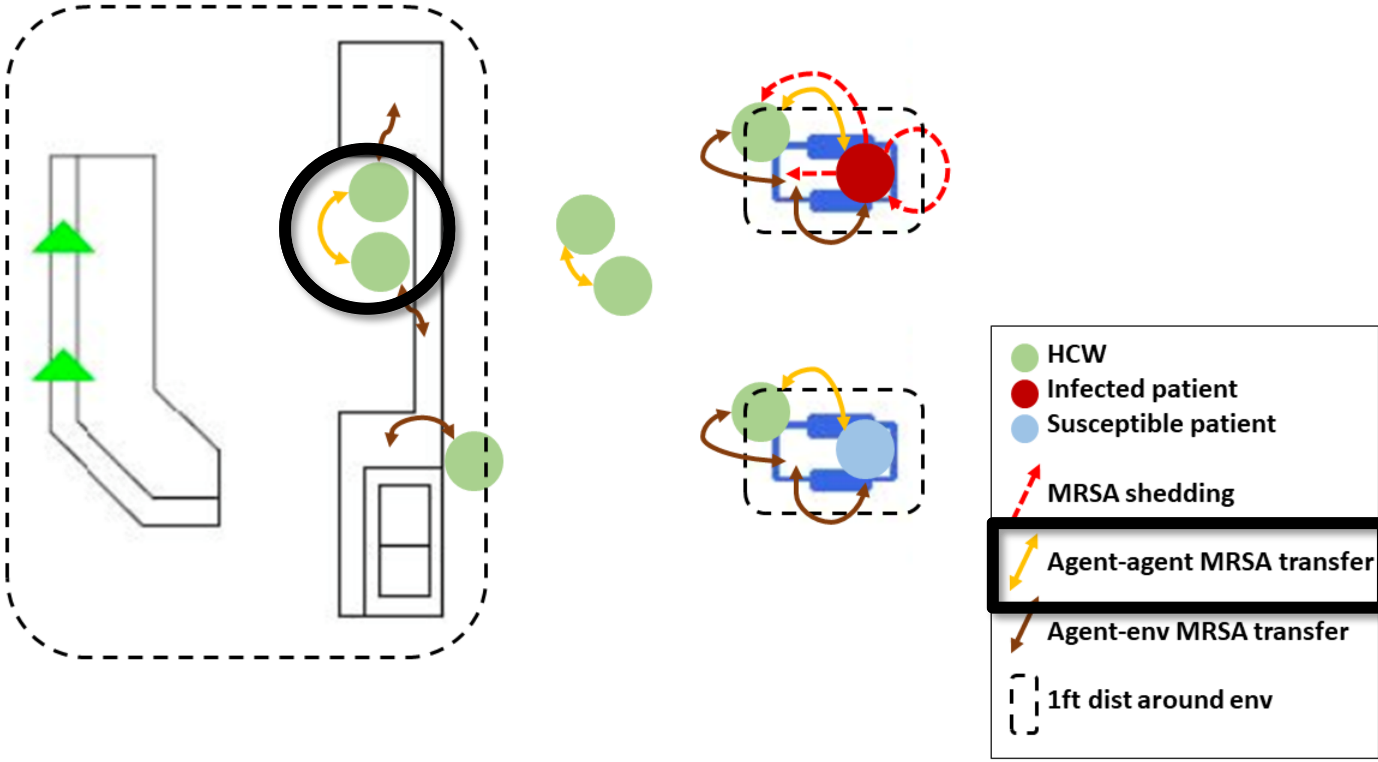

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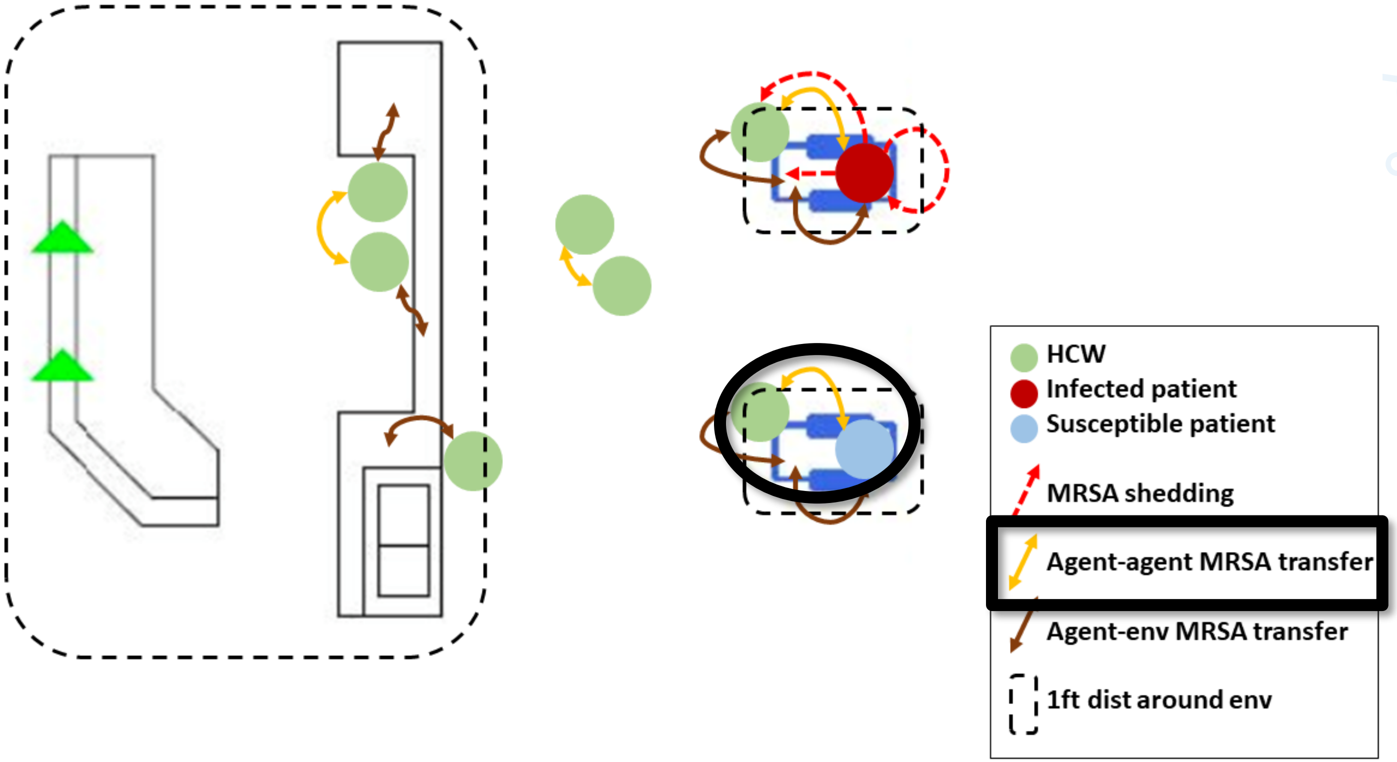

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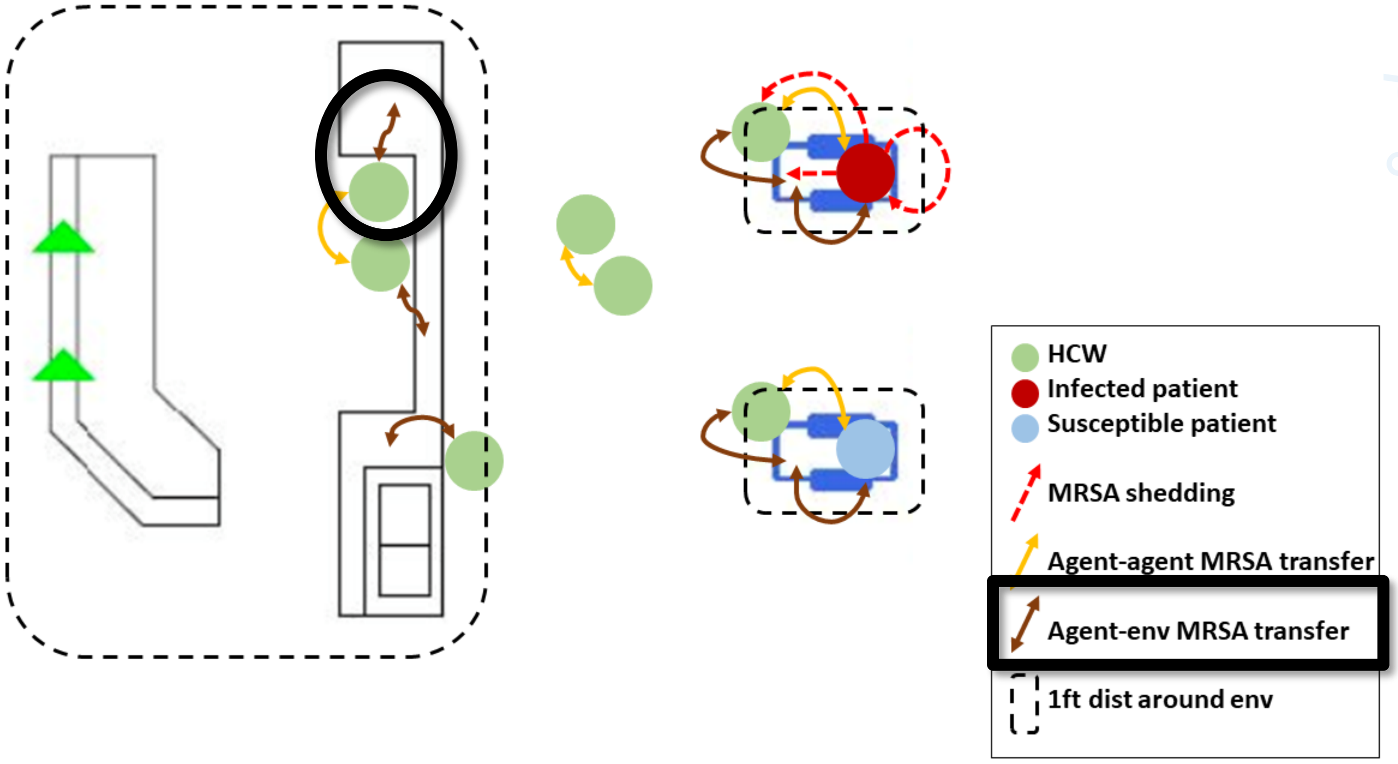

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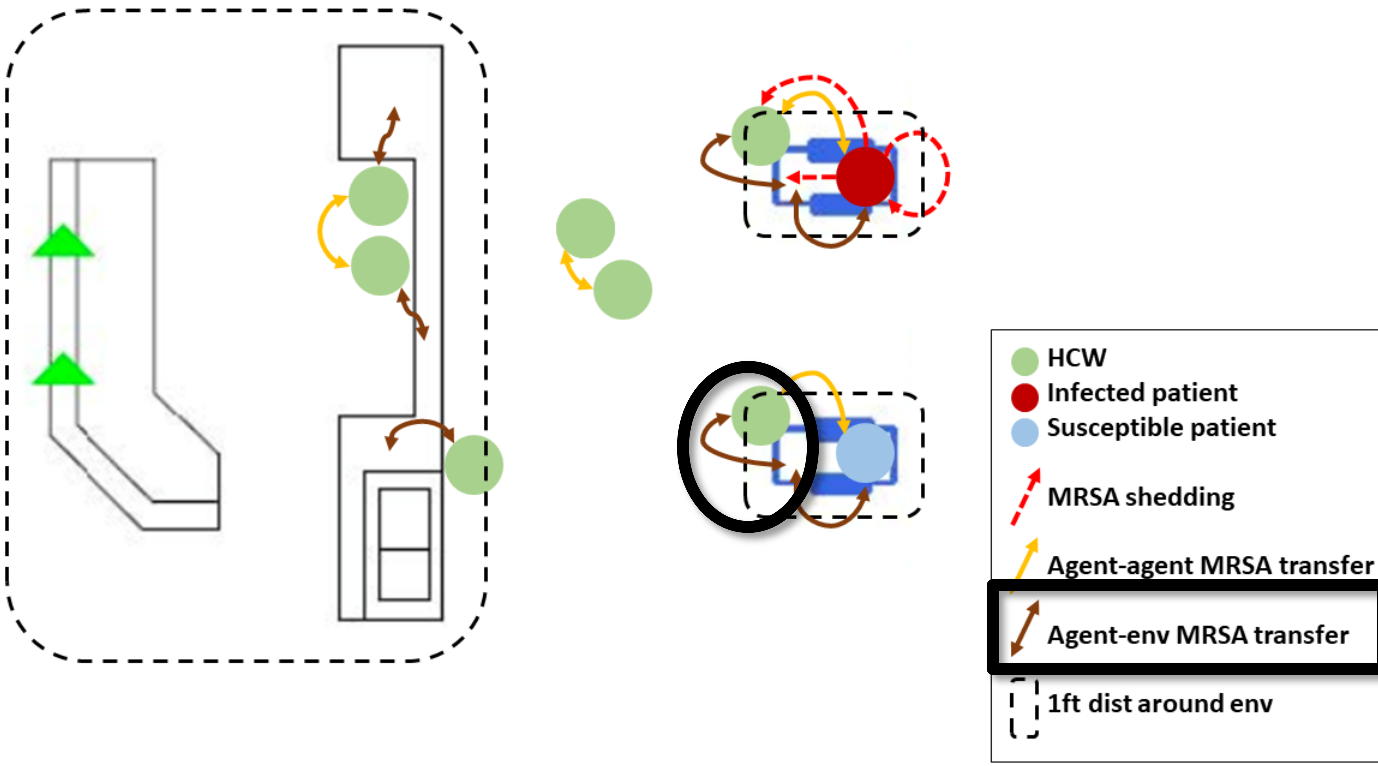

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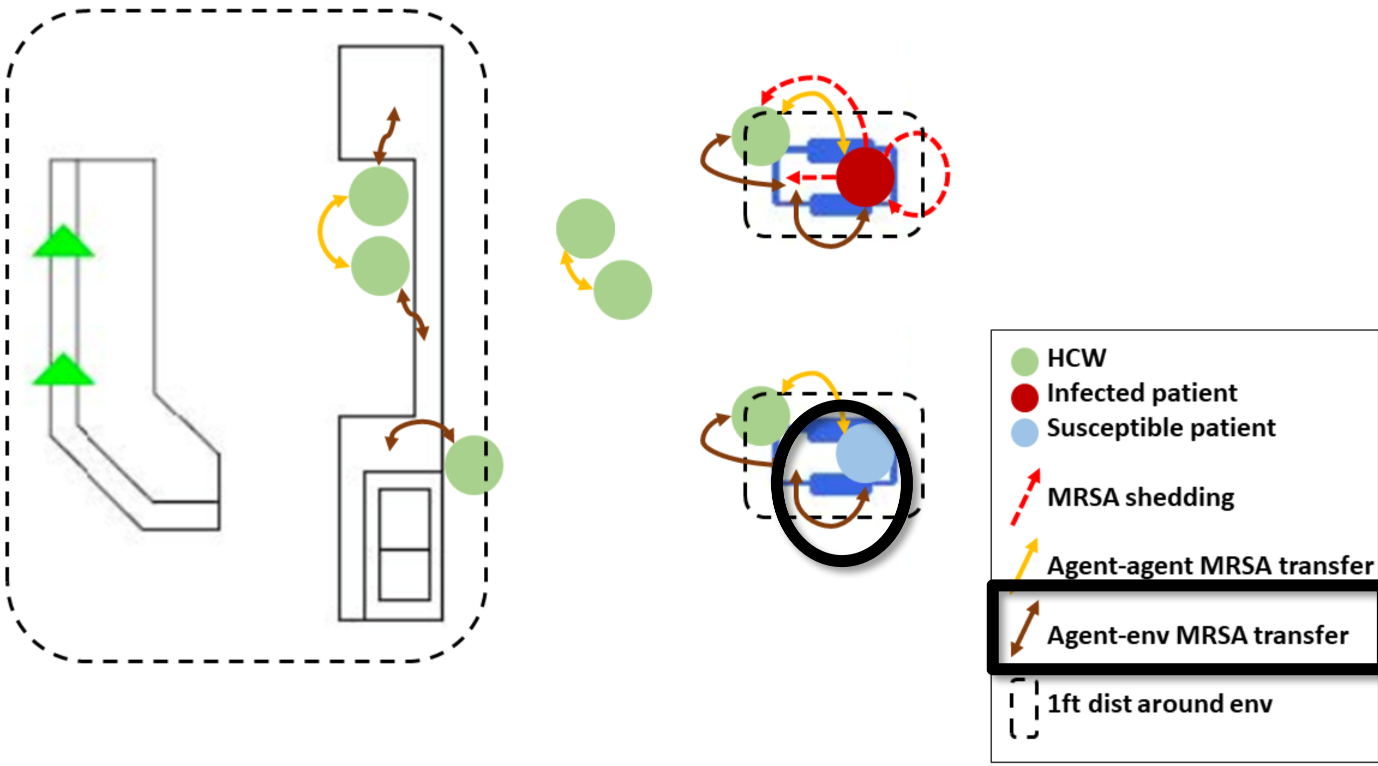

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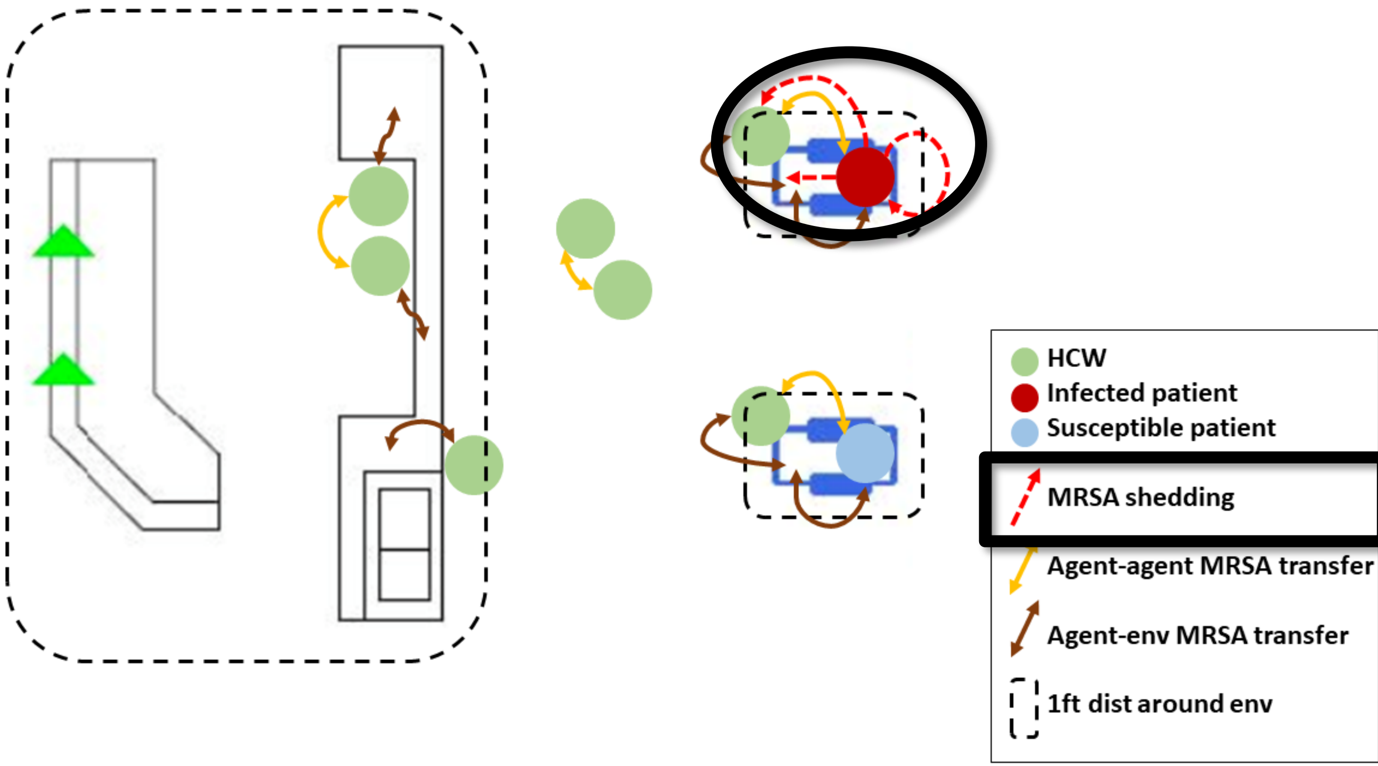

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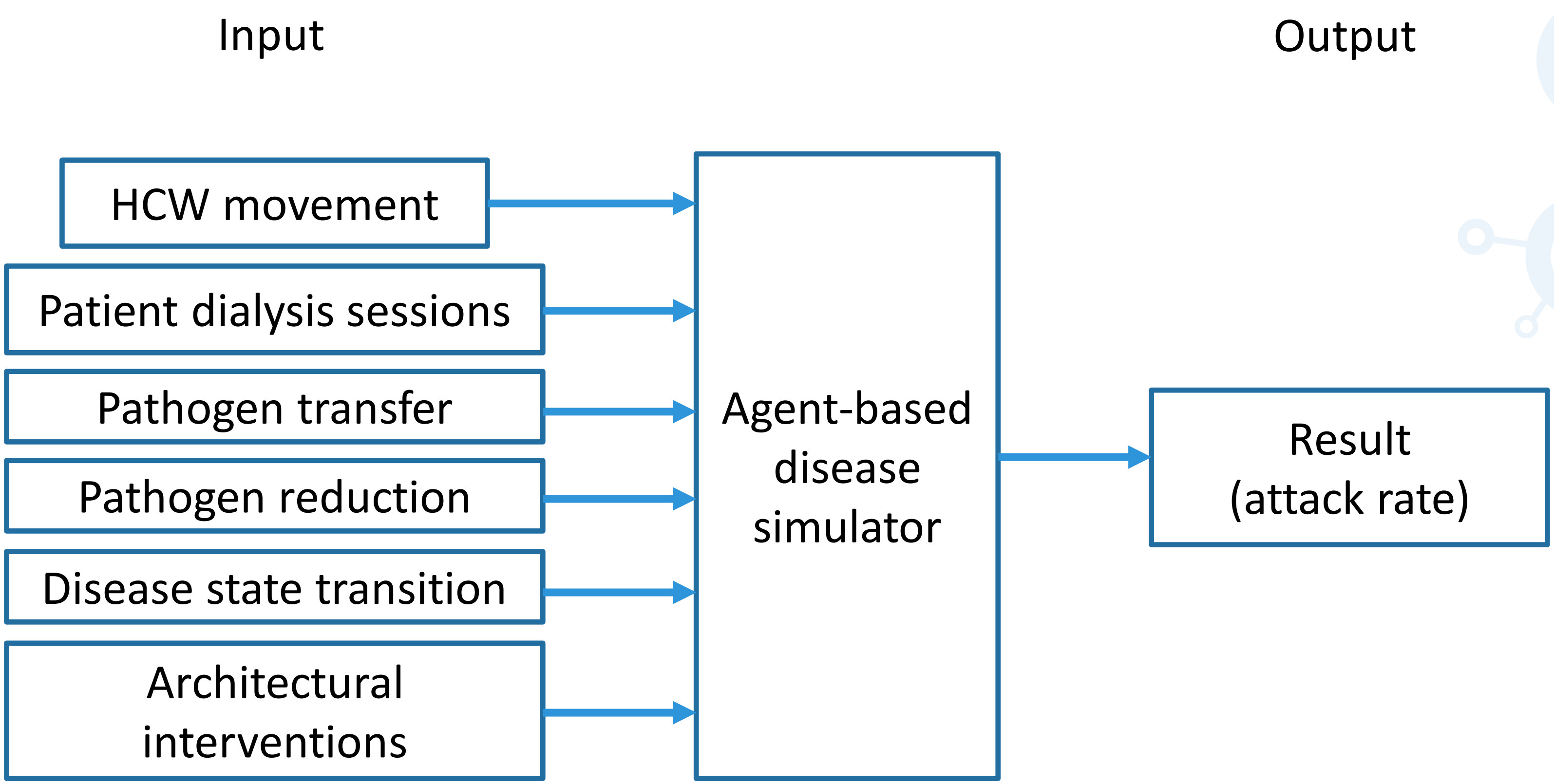
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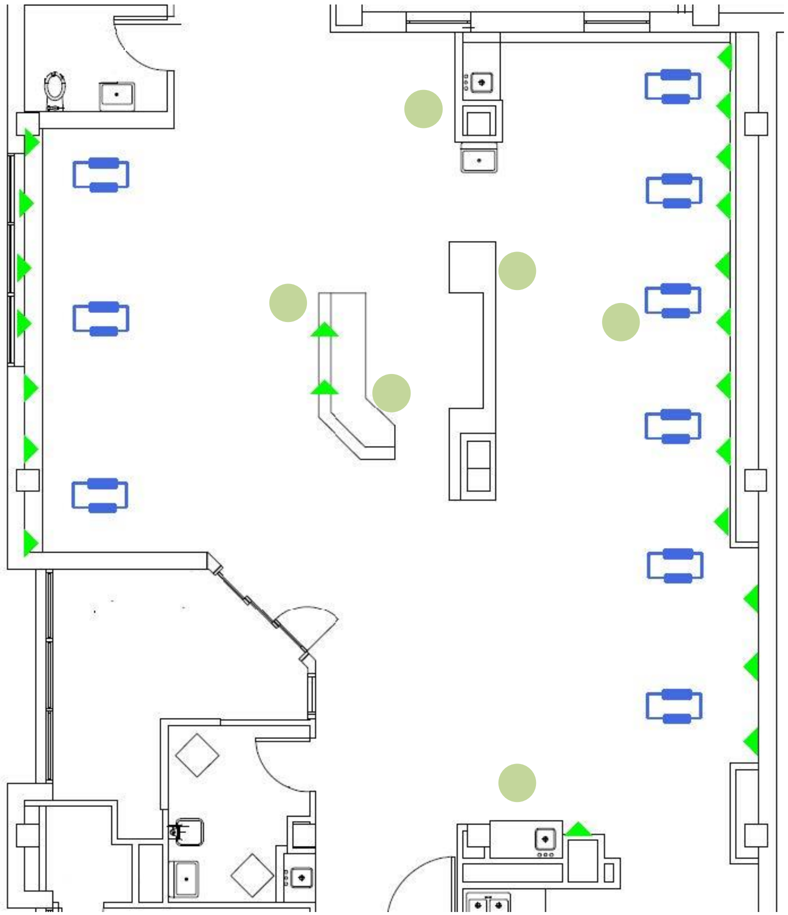
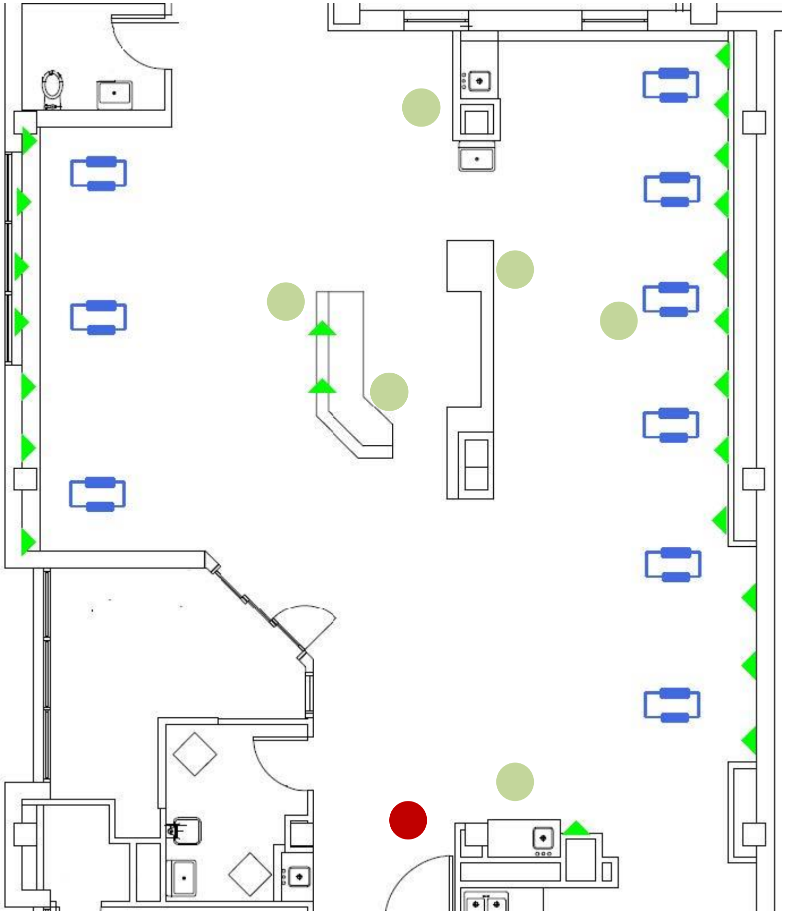
Dialysis unit

In the morning



Dialysis unit

MRSA infected patient enters



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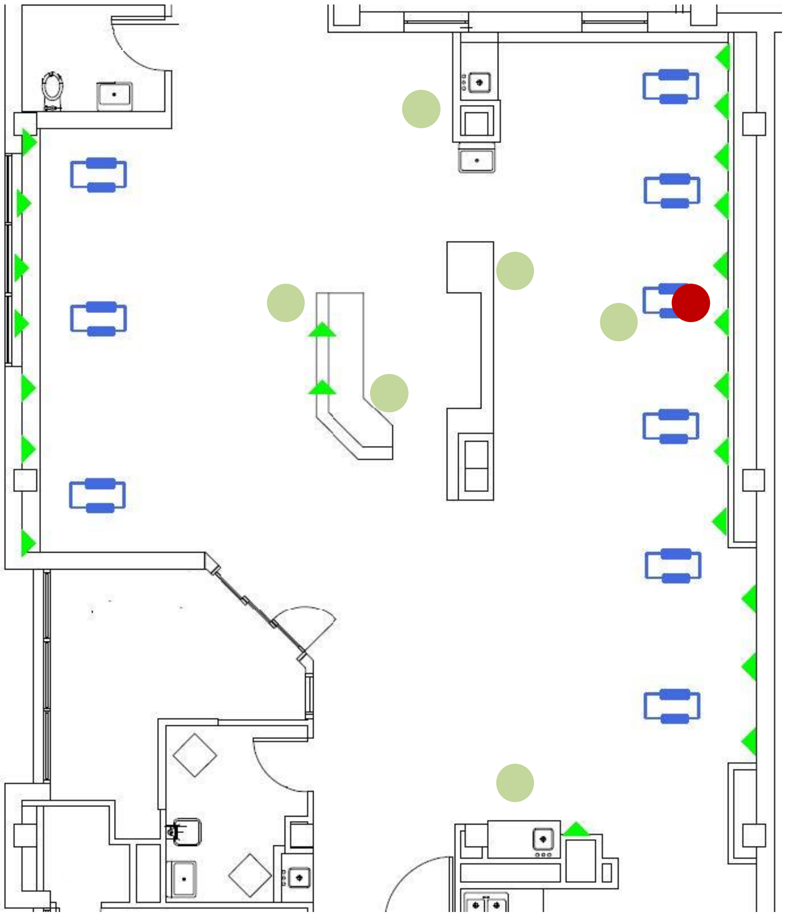

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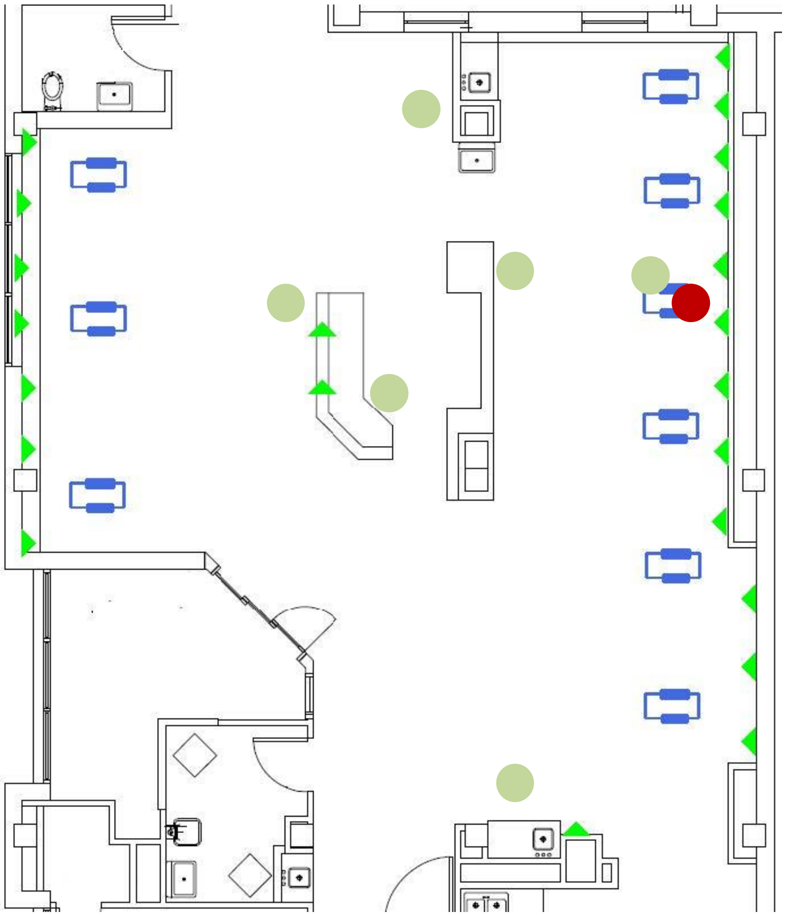
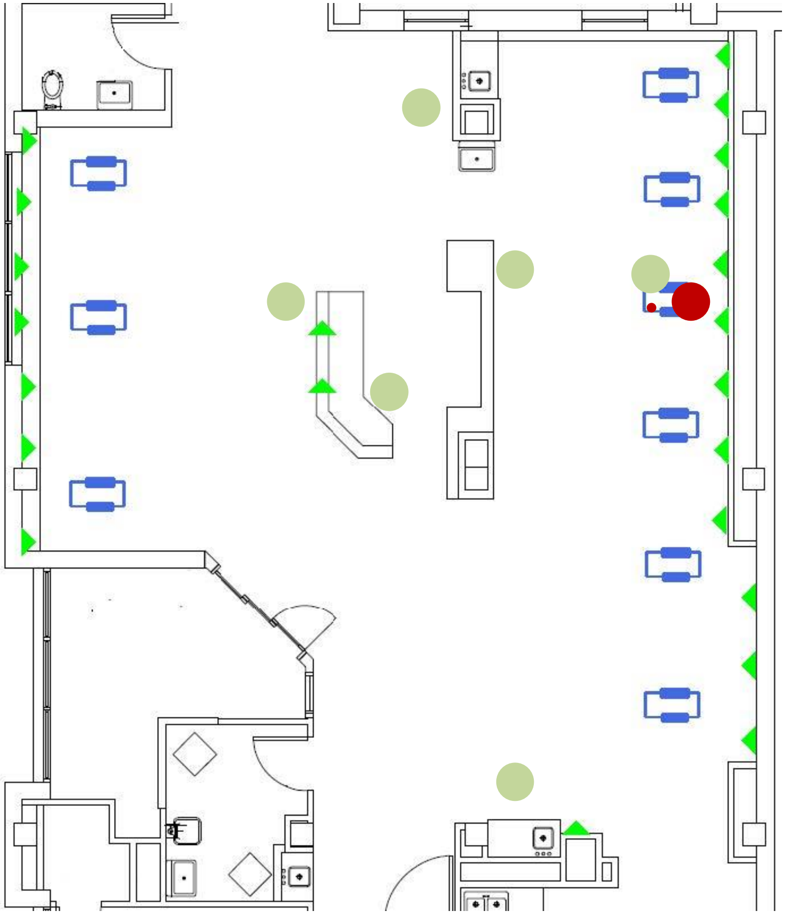
Dialysis unit

MRSA infected patient enters



Dialysis unit

MRSA infected patient start shedding



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Dialysis unit

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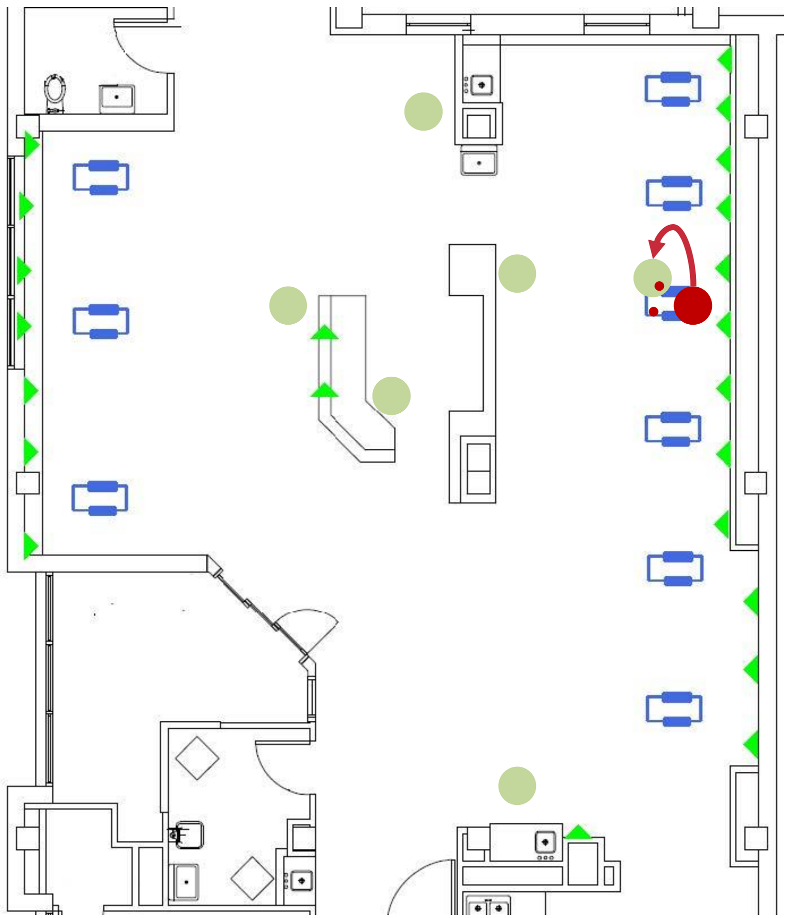

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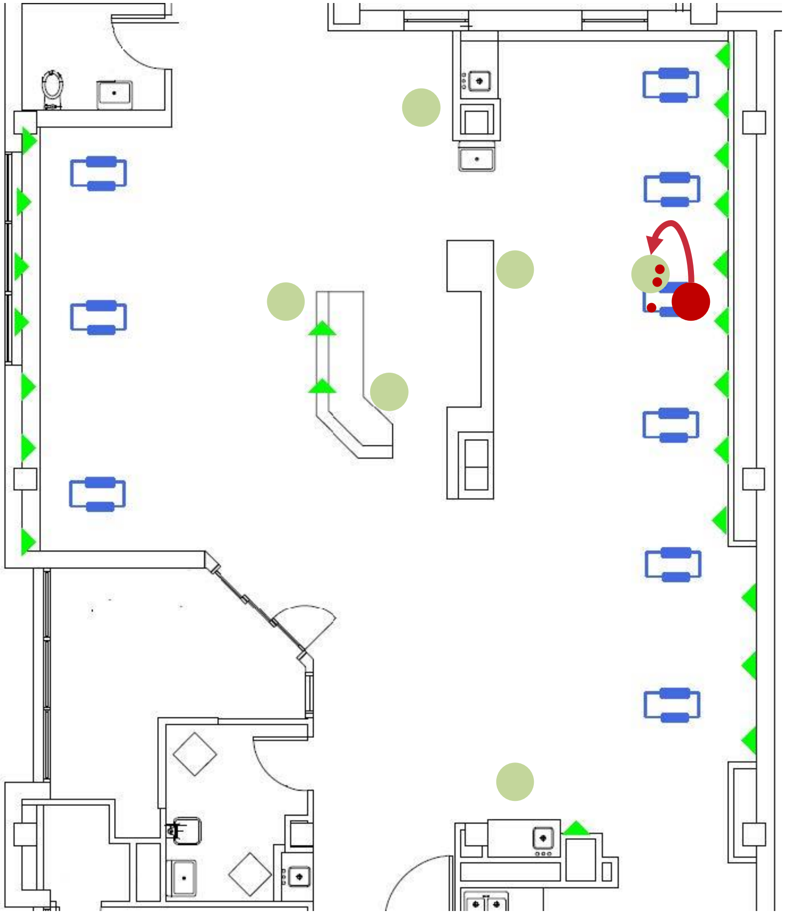
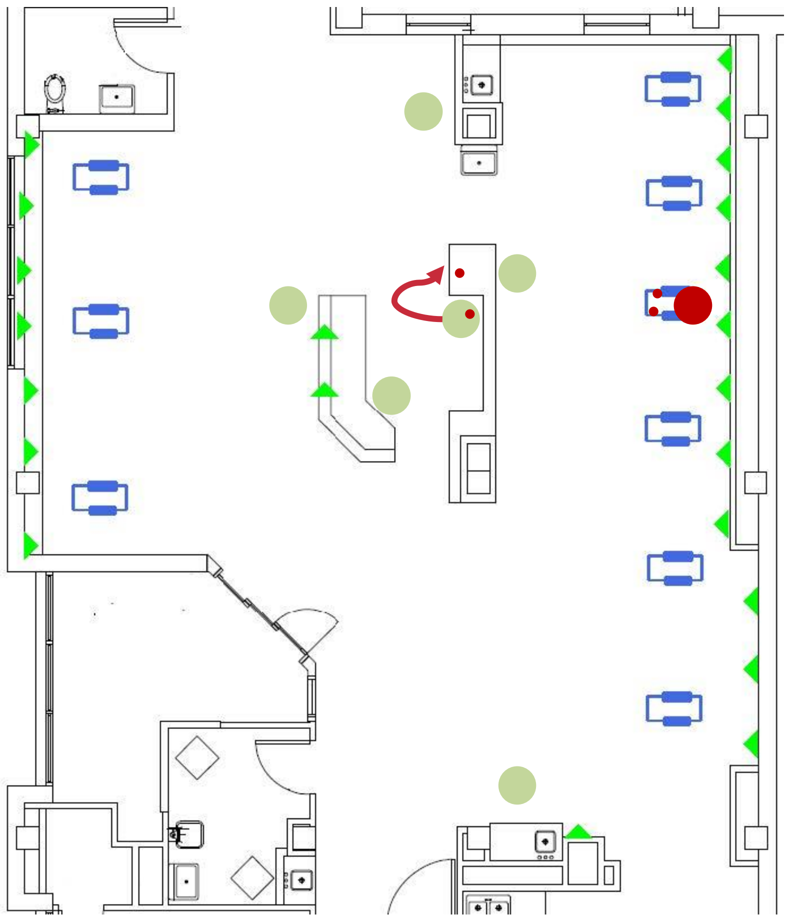


Dialysis unit

Colonized HCW drops off pathogen at the nurses station



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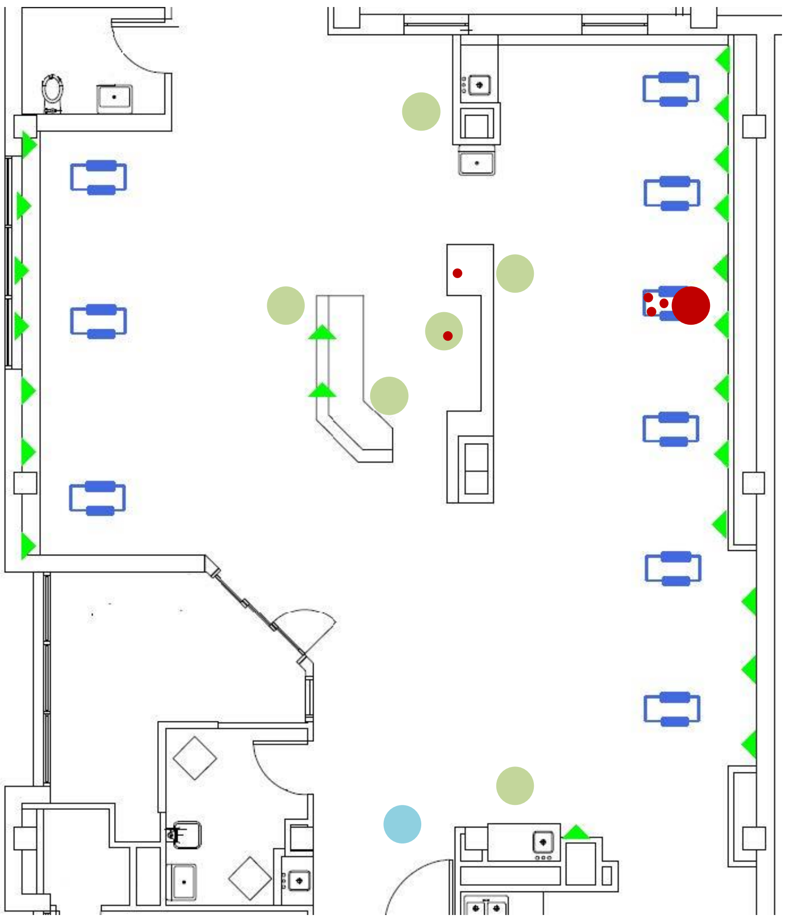
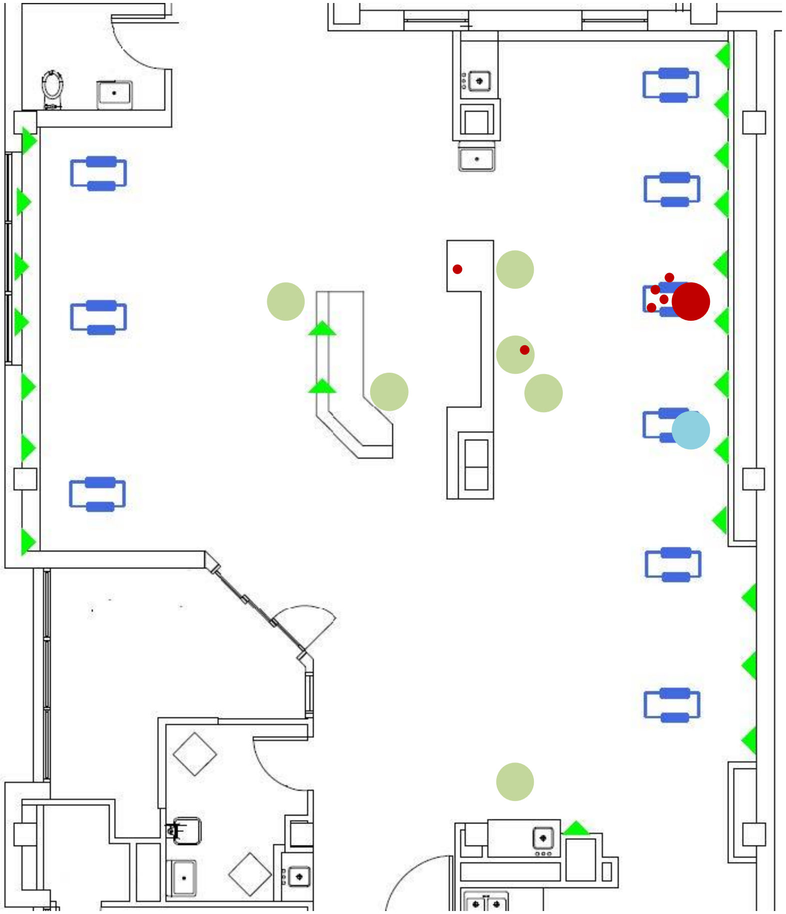
Dialysis unit

Another patient enters



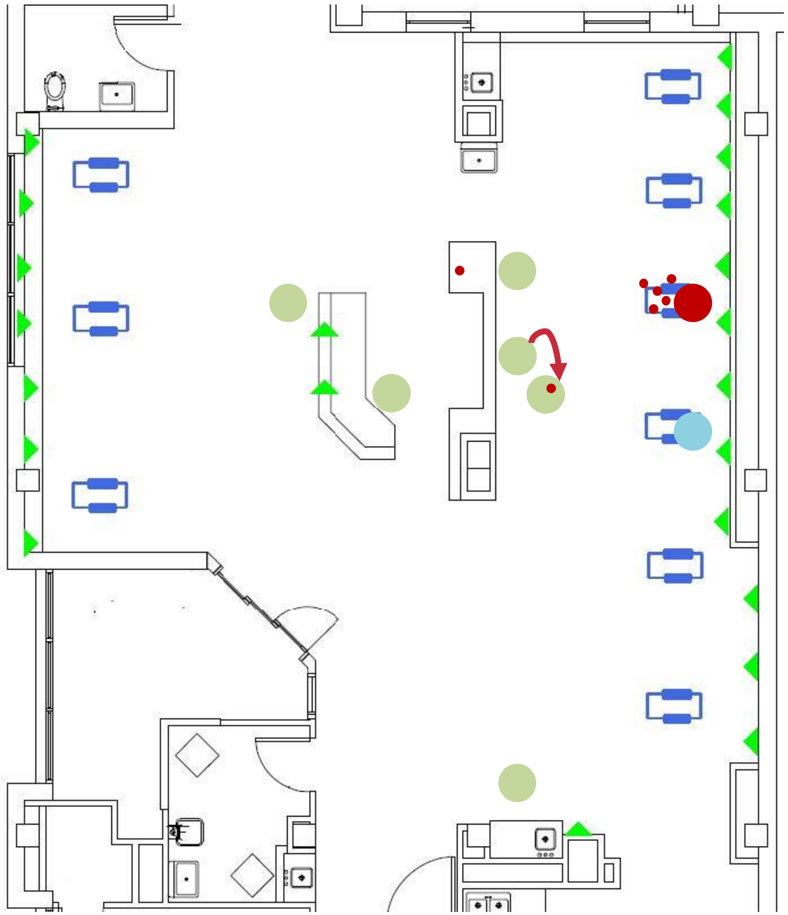
Dialysis unit

Another patient enters



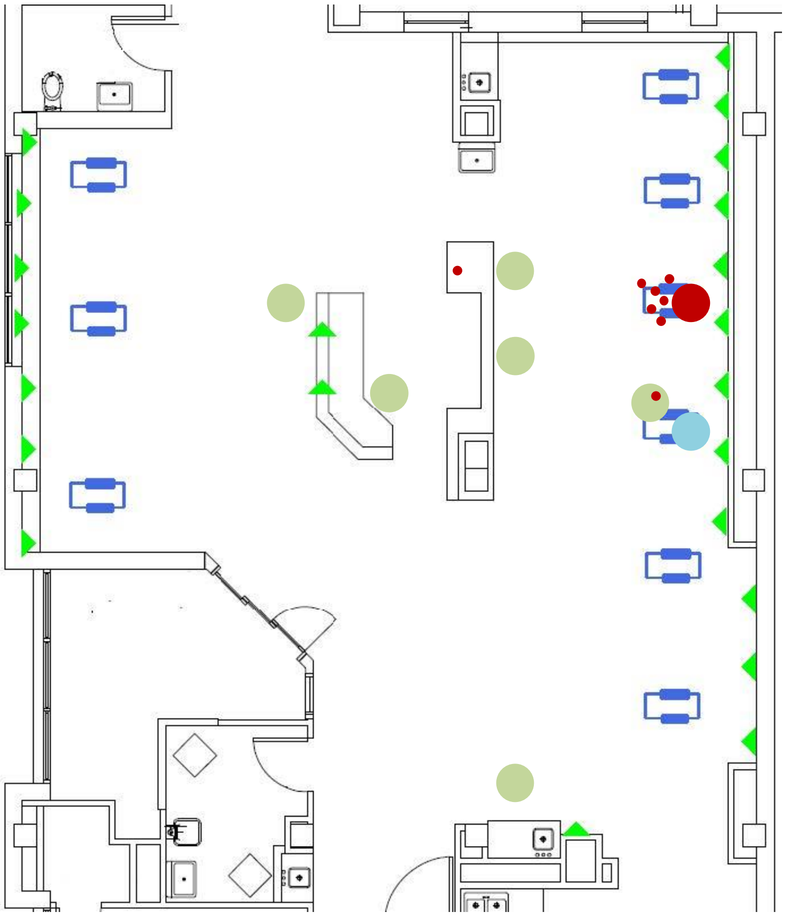
Dialysis unit

Another patient enters



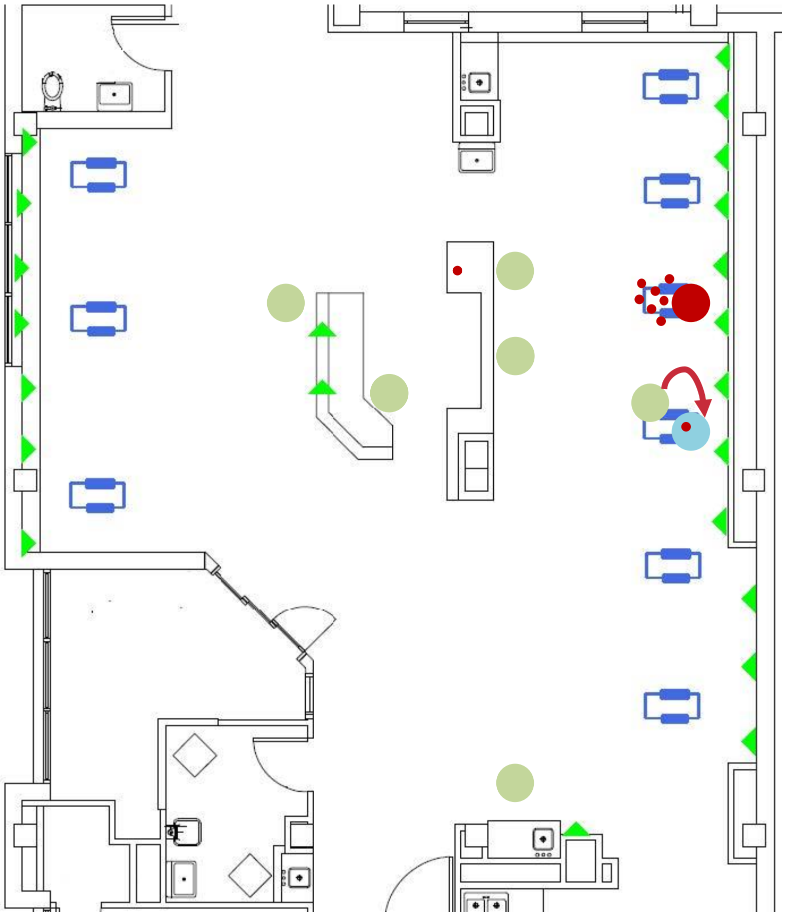
Dialysis unit

Another patient enters



Dialysis unit

MRSA transfers from HCW to patient



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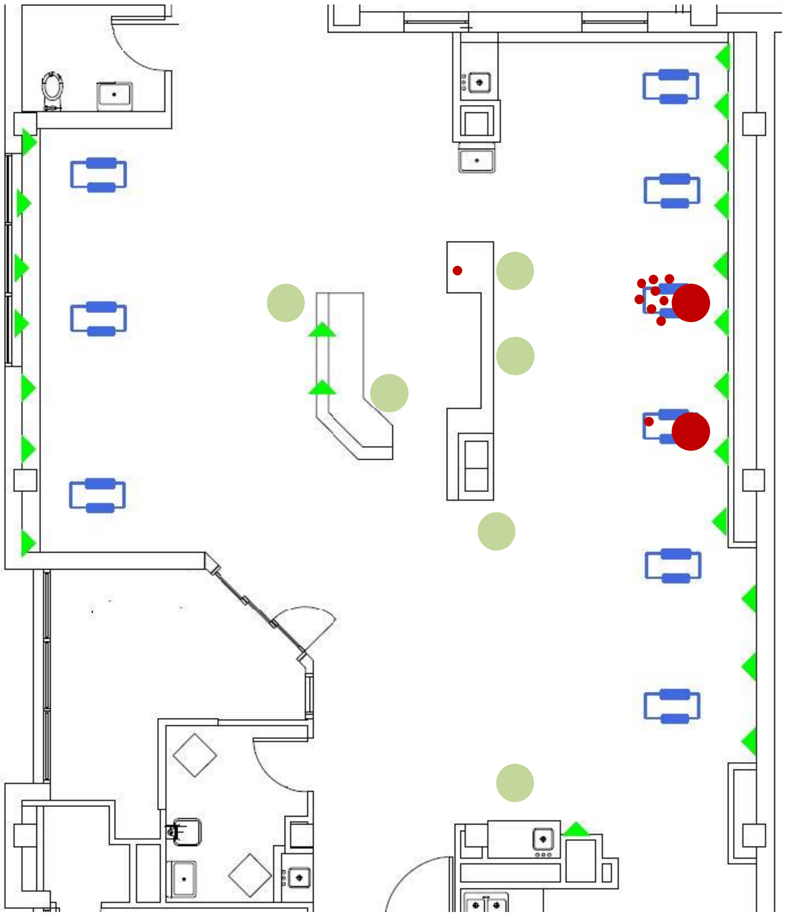
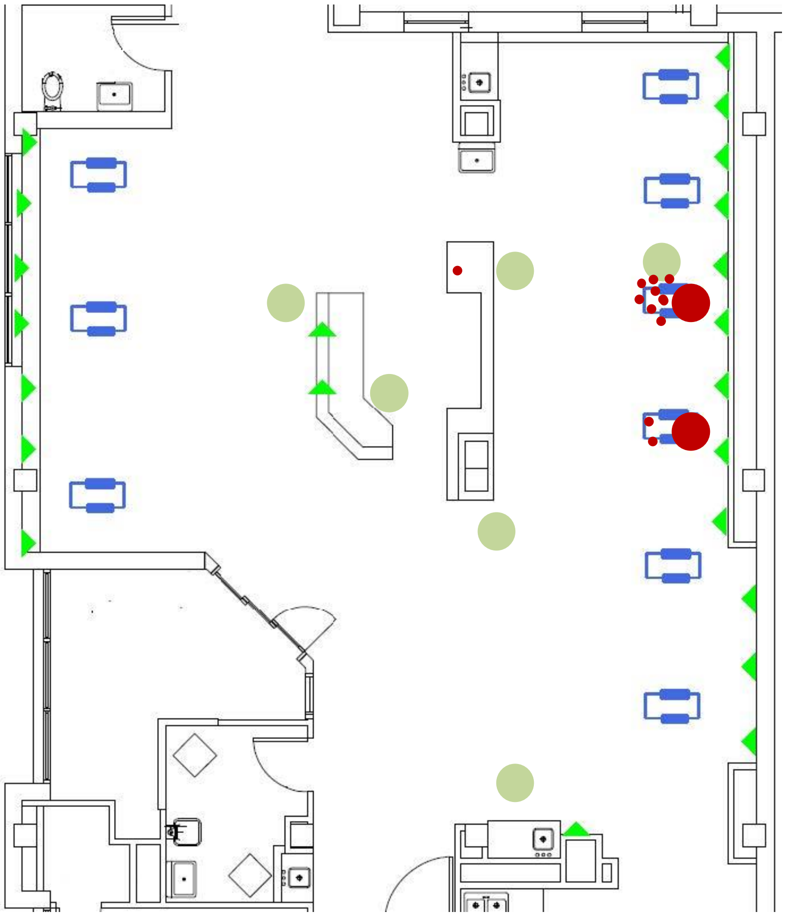
Dialysis unit

Patient gets infected to MRSA



Dialysis unit

MRSA concentration in the unit increases



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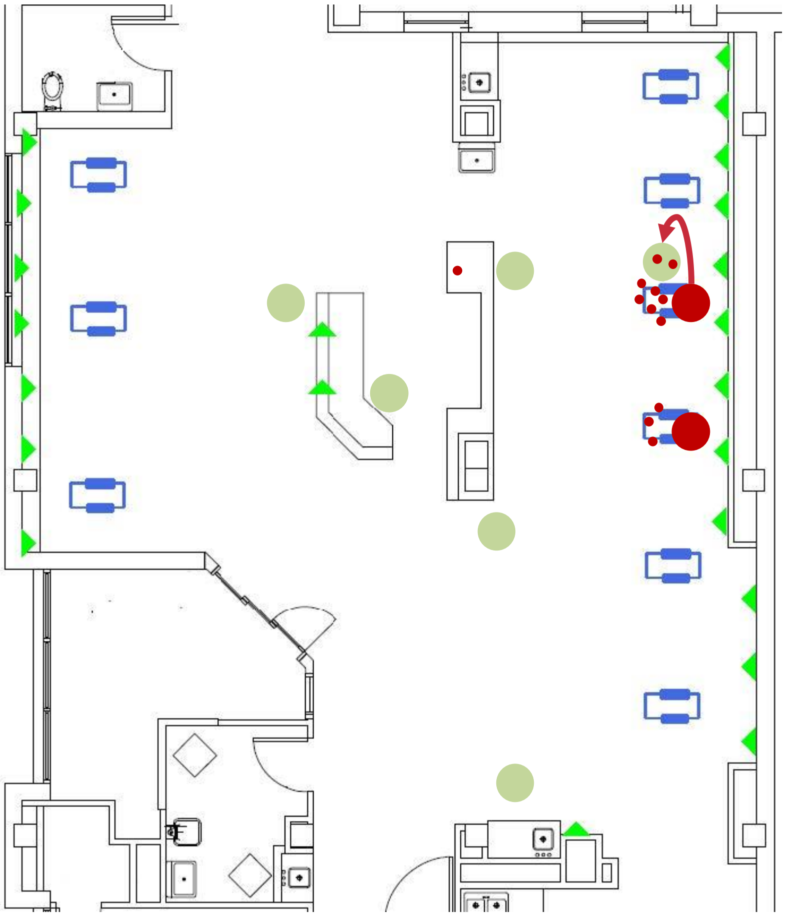

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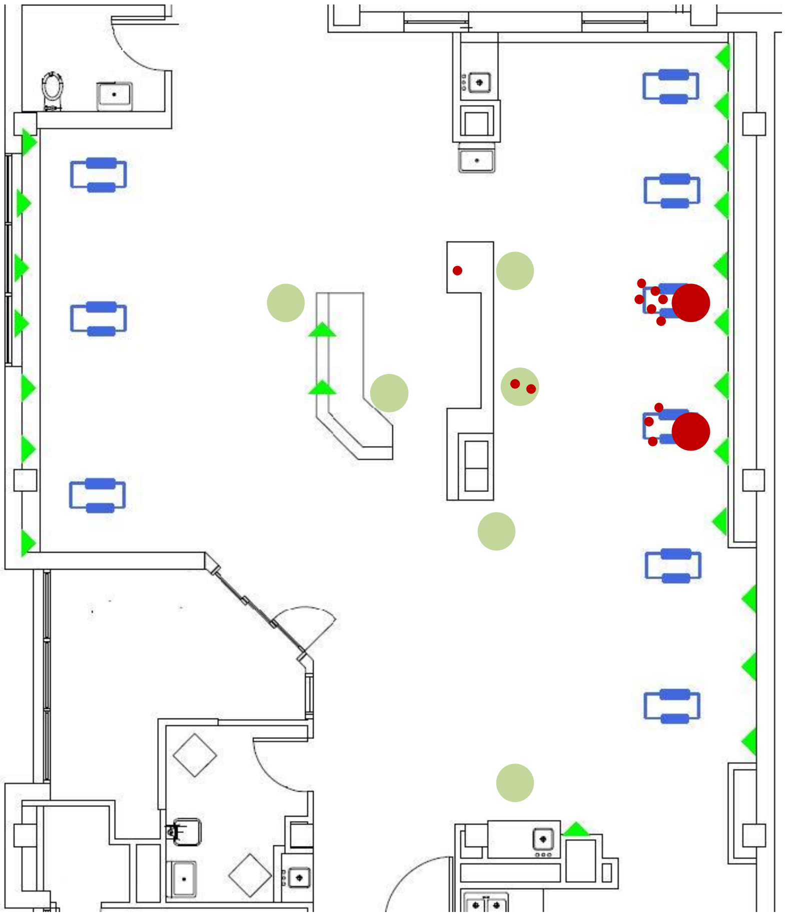

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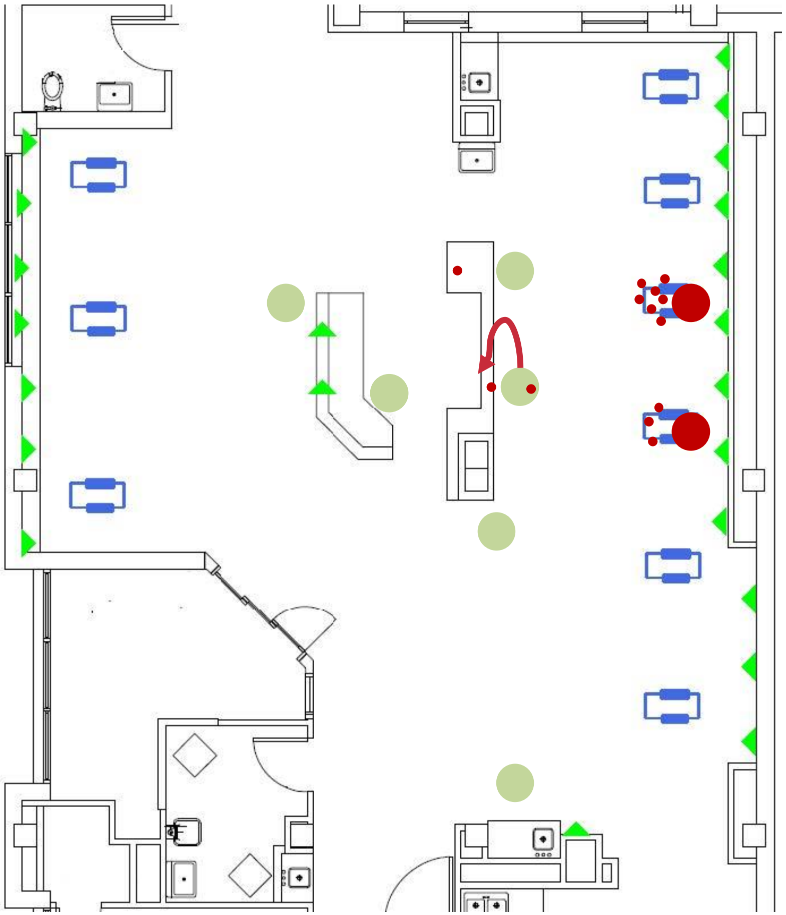
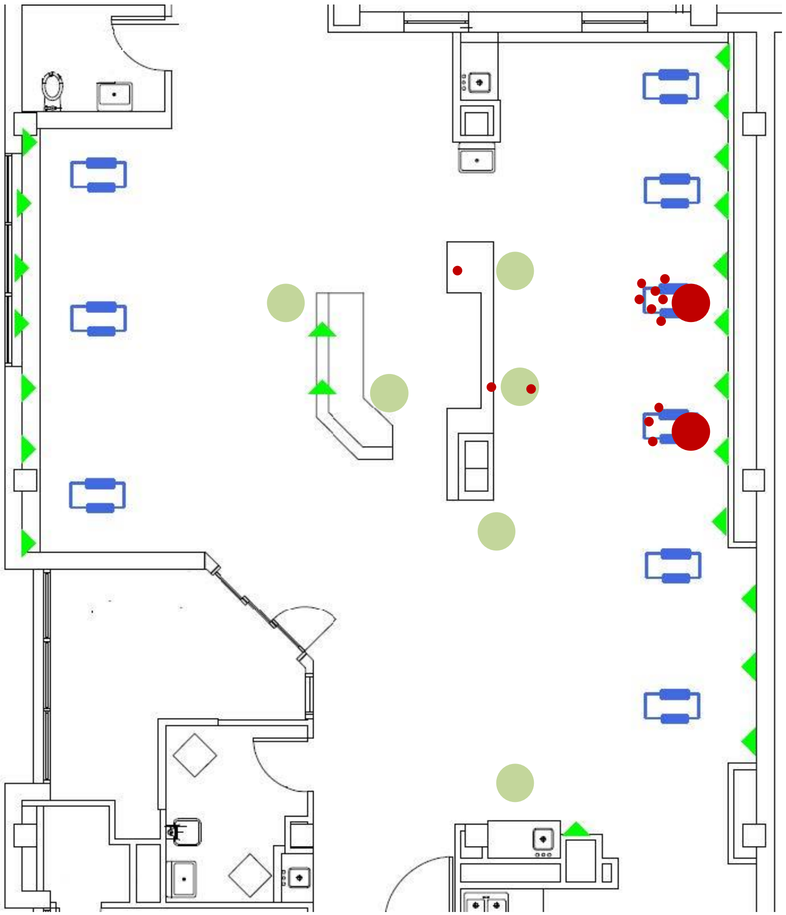


- How to reduce the spread of MRSA?

Dialysis unit

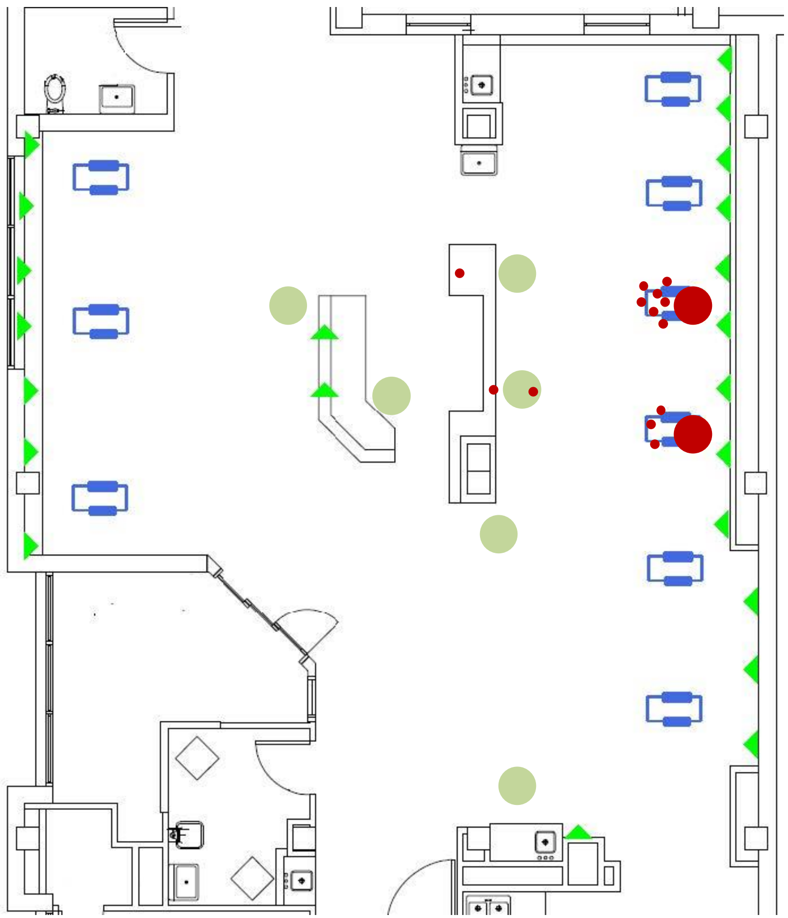
MRSA concentration in the unit increases



- How to reduce the spread of MRSA?
  - HCW Hand hygiene
  - Surface cleaning

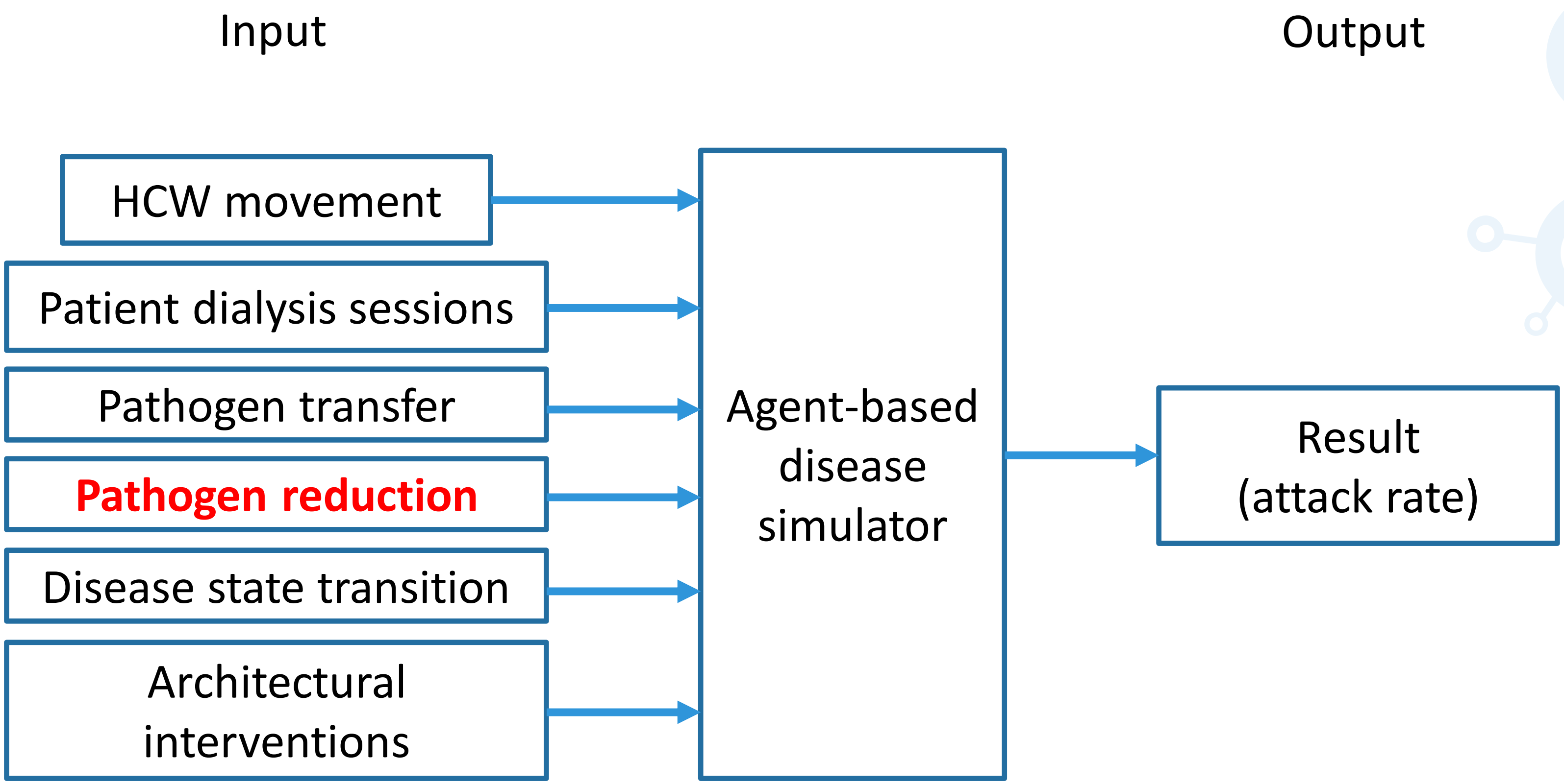
Dialysis unit

MRSA concentration in the unit increases



- How to reduce the spread of MRSA?
- Any simple architectural changes that reduce the spread of MRSA?

Overview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Result (attack rate)

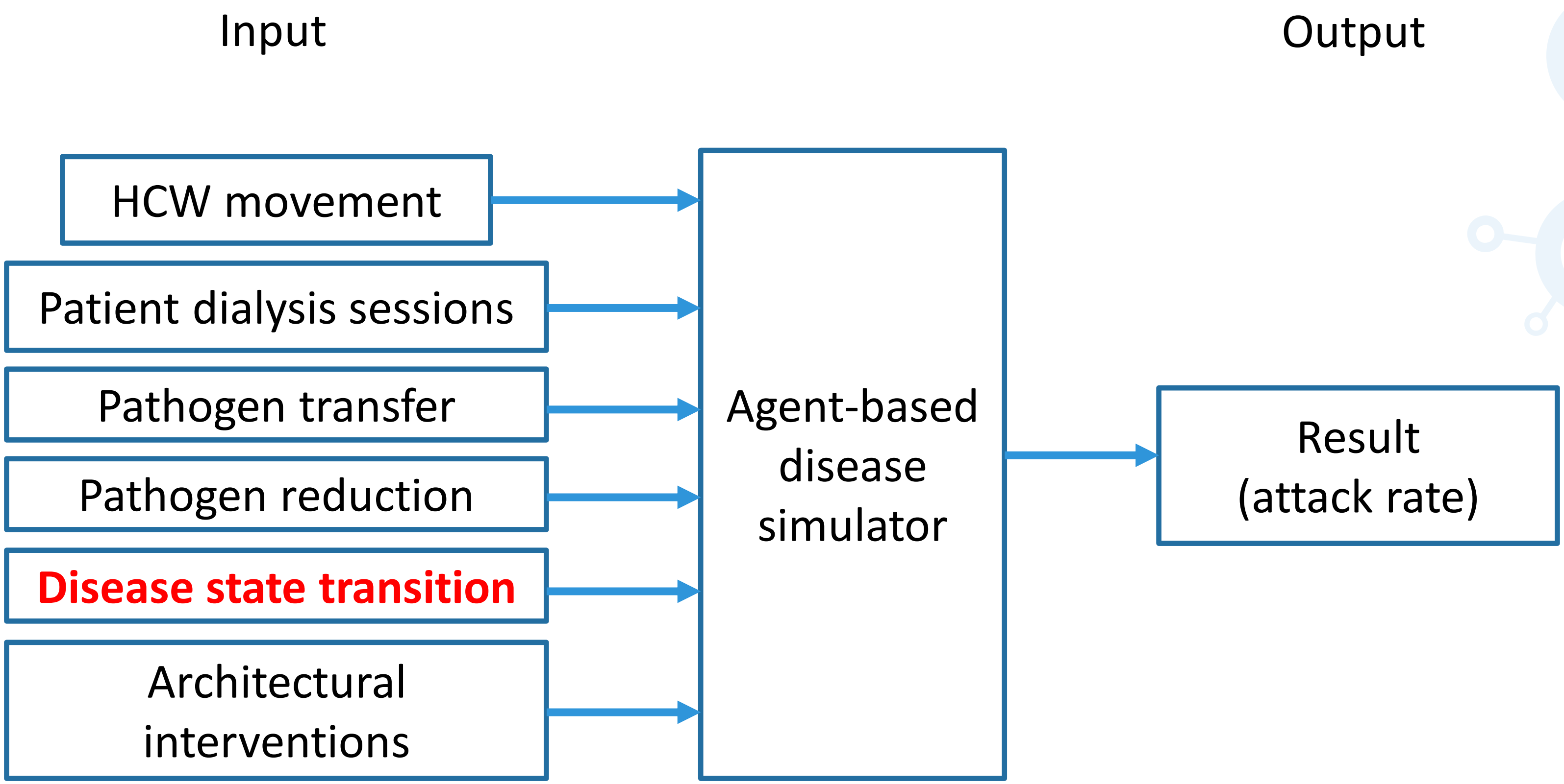
Simulating the spread of MRSA in the dialysis unit

Pathogen reduction

- MRSA pathogen could be removed from environments via three distinct mechanisms
  - HCWs performing hand hygiene
  - Environmental cleaning
  - Natural decay

E. Girou et al.,"Efficacy of hand rubbing with alcohol based solution versus standard handwashing with antiseptic soap: randomised clinical trial," Bmj, vol.325, no.7360, p.362, 2002
M. N. Monsalve et al., "Do peer effects improve hand hygiene adherence among healthcare workers?" Infection Control & Hospital Epidemiology, vol.35, no.10, pp.1277–1285, 2014
O. Sherlock et al., "Is it really clean? An evaluation of the efficacy of four methods for determining hospital cleanliness," Journal of Hospital Infection, vol.72, no.2, pp.140–146, 2009

Overview


Input
Output
HCW movement
Patient dialysis sessions
Pathogen transfer
Pathogen reduction
Disease state transition
Architectural interventions
Agent-based disease simulator
Result (attack rate)

Simulating the spread of MRSA in the dialysis unit

Disease state transition

- Colonization may result in the patient becoming infected
- Dose-response functions
  - Input: MRSA concentration on patient's skin
  - Output: probability of infection
- Explored two dose-response models
  - Linear: $\mathrm{f(x)} = \pi x$
  - Exponential: $\mathrm{f(x)} = 1 - e^{-\pi x}$
  - π is the infectivity of the pathogen

N. Plipat et al., "The dynamics of methicillin-resistant Staphylococcus aureus exposure in a hospital model and the potential for environmental intervention," BMC infectious diseases, vol.13, no.1, p.595, 2013
A. F. Brouwer et al., "Dose-response relationships for environmentally mediated infectious disease transmission models," PLOS Computational Biology, vol.13, no.4, pp.1–28, 04 2017

Simulating the spread of MRSA in the dialysis unit

Baseline simulation parameters

TABLE III
BASELINE SIMULATION PARAMETERS

Parameter	Symbol	Value	Ref
Shedding rate ($cfu/cm^2/8s$)	α	0.001333	[5]
Die-off rate on skin ($/8s$)	μ_{sk}	0.000471	[5]
Die-off rate on environments ($/8s$)	μ_{np}	0.000027	[5]
Transfer efficiency: skin-skin	$\rho_{sk\text{-}sk}$	0.35	[5]
Transfer efficiency: skin-env	$\rho_{sk\text{-}np}$	0.4	[5]
Area of patient's exposed skin (cm^2)	A_{pt}	2000	[5]
Area of HCW's exposed skin (cm^2)	A_{hcw}	150	-
Area of hand contact surface (cm^2)	A_h	150	[5]
Area of chair surface (cm^2)	A_{ch}	3600	-
Area of nurses' station (cm^2)	A_{ns}	41000	-
Decontamination efficacy	ϵ	0.5	[17]
Hand hygiene compliance	γ	0.279	[12]
Hand hygiene efficacy	λ	0.83	[16]
Rate of HCW-HCW contact	τ_{hcw}	0.05	-
Infection duration	d	10	[7]
Dose-response function	$f(x)$	$exponential$	[18]
MRSA Infectivity	π	$\frac{1}{7.5M}$	-

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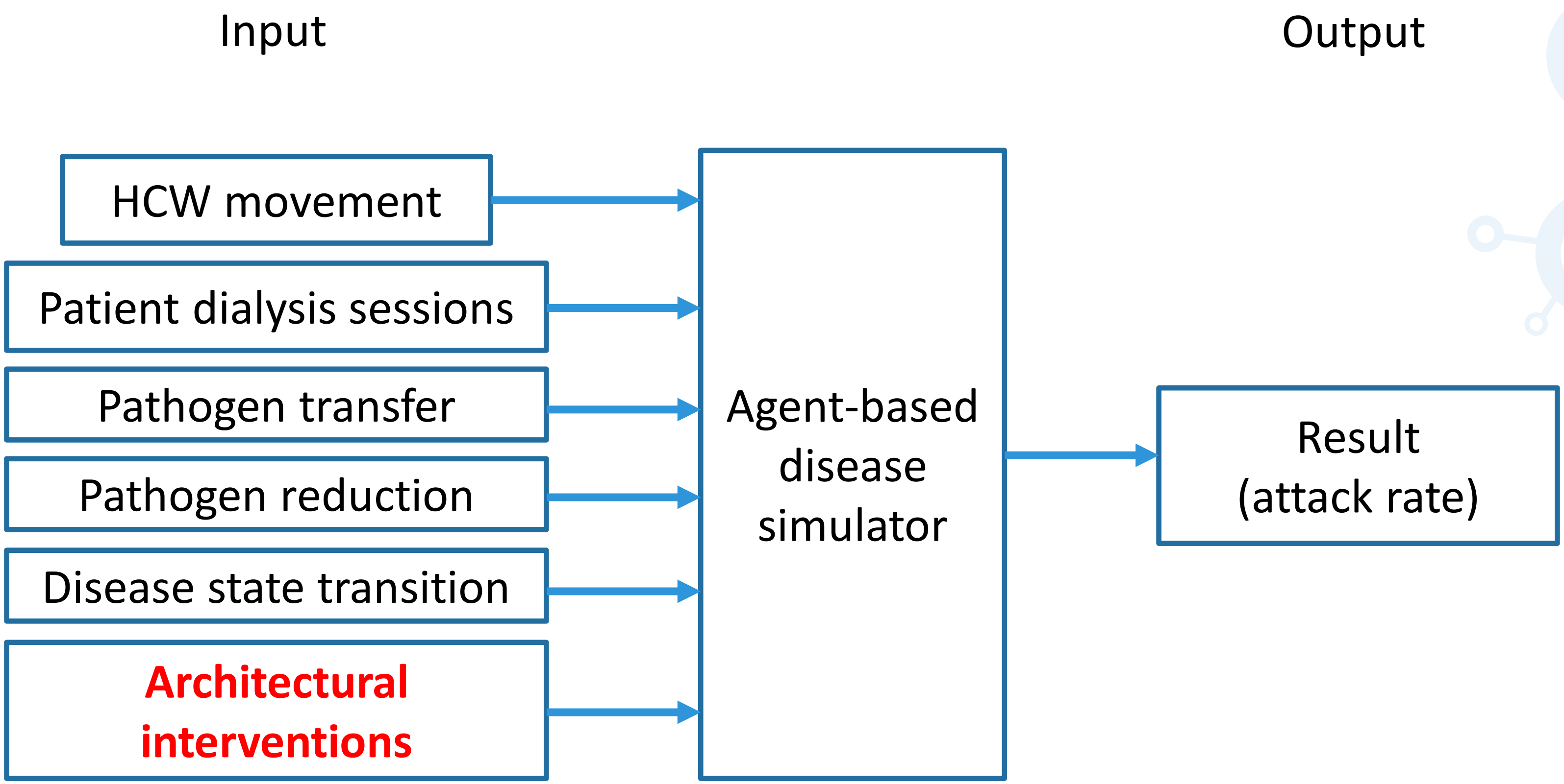
Overview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Modeling architectural changes

Two simple, low-cost architectural changes

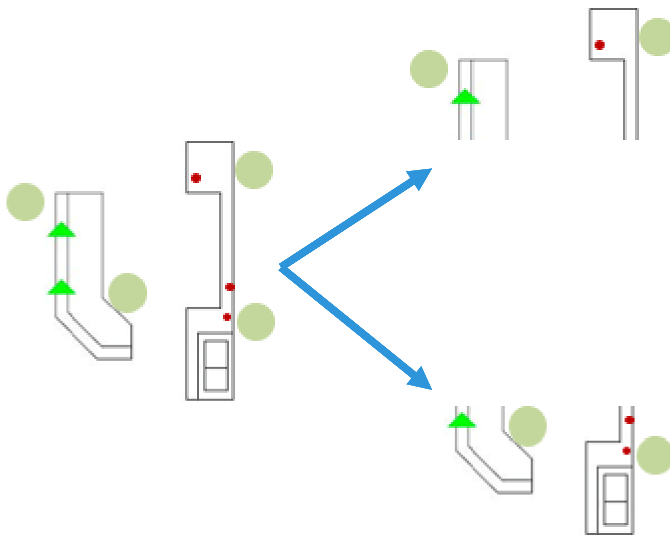
- No architectural change (Policy 0)
- Architecture change 1: splitting the nurses' station into two stations (Policy 1-3)
  - Idea: 'staff cohorting' used in infection control to reduce infection spread
- Architecture change 2: doubling the Surface Area of the Nurses Station (Policy 4)
  - Idea: 'dilute' MRSA concentration at the nurses' station

E. M. Jochimsen et al., "Control of vancomycin-resistant enterococci at a community hospital: Efficacy of patient and staff cohorting," Infection Control & Hospital Epidemiology, vol.20, no.2, pp.106–109, 1999

Modeling architectural changes

Architecture change 1: split into two stations

- Split the nurses' station NS into two stations NS_1 and NS_2
  - Partition HCWs equitably into two groups H_1 and H_2 (3 policies)
  - Contacts between $h \in H_1$ and $h` \in H_2$ at NS is removed
  - Hypothesis: reducing HCW contacts may reduce spread of MRSA



Modeling architectural changes

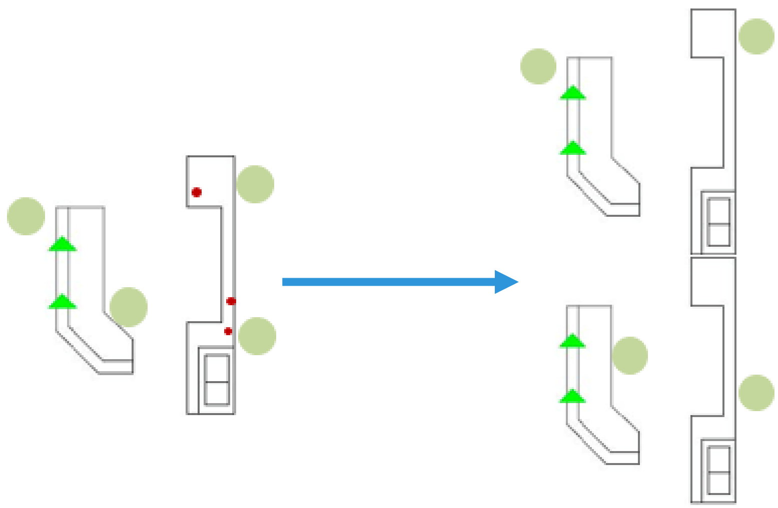
Architecture change 1: split into two stations

- Split the nurses' station NS into two stations NS_1 and NS_2
  - Partition HCWs equitably into two groups H_1 and H_2 (3 policies)
  - Contacts between h $\in H_1$ and h` $\in H_2$ at NS is removed
  - Hypothesis: reducing HCW contacts may reduce spread of MRSA
- How to partition HCWs?
  - Randomly partition HCWs: Random Grouping (Policy 1)
  - Greatest reduction in contact duration between H_1 and H_2
    - NS: Max Bisection on G_{ns} (Policy 2)
    - Anywhere: Max Bisection on G_{all} (Policy 3)

Modeling architectural changes

Architecture change 2: double the surface area

- Hypothesis: diluting the level of surface contamination at the nurses' station may reduce spread of MRSA (Policy 4)



Modeling architectural changes

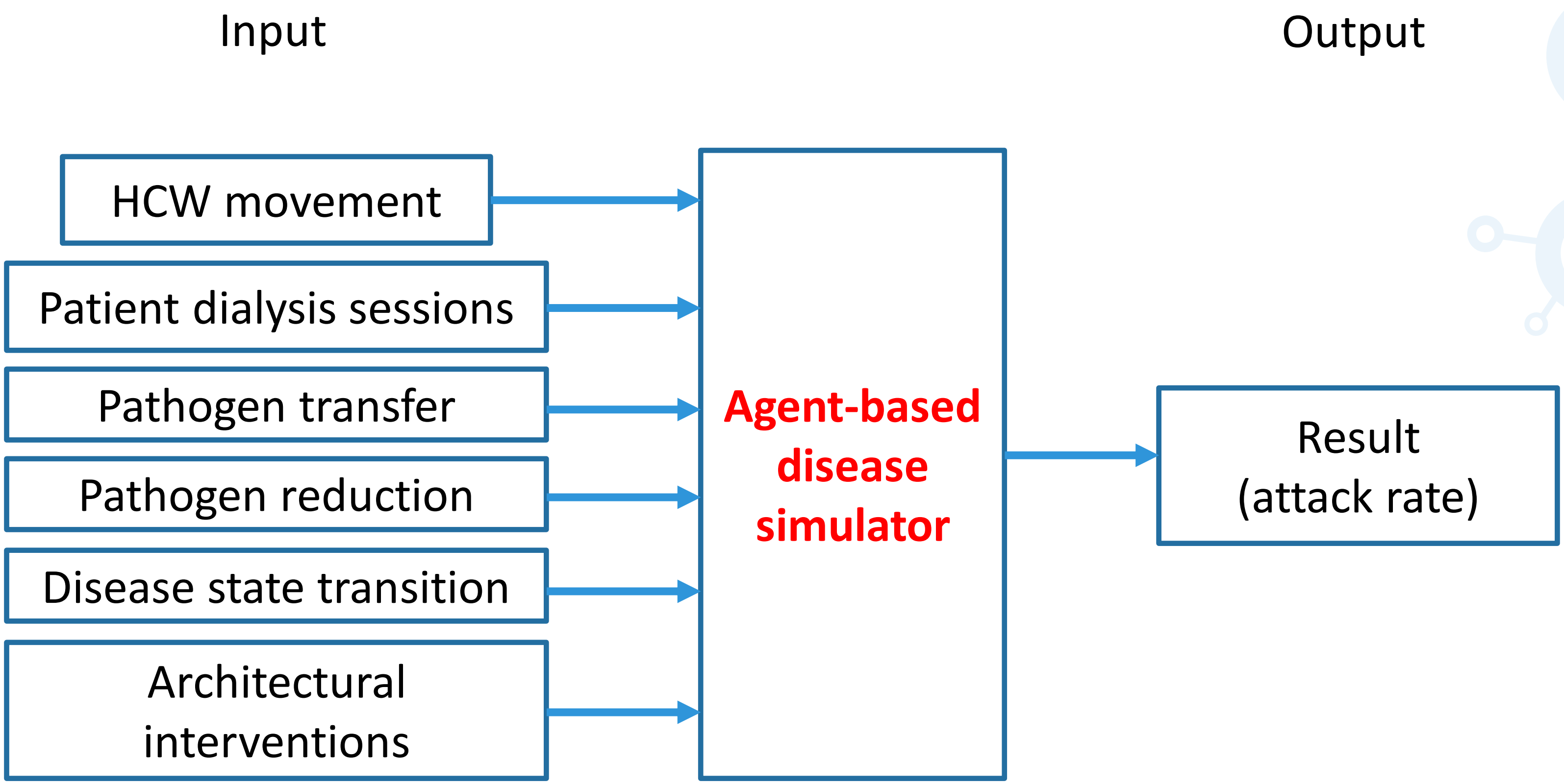
Summary

TABLE II

NURSES STATION ARCHITECTURE CHANGE POLICIES

Policy	Architecture Change	HCW Grouping
0	None (baseline)	No Grouping
1	Split into two stations	Random Grouping
2	Split into two stations	Max Bisection on G_{ns}
3	Split into two stations	Max Bisection on G_{all}
4	Double the surface area	No Grouping

Overview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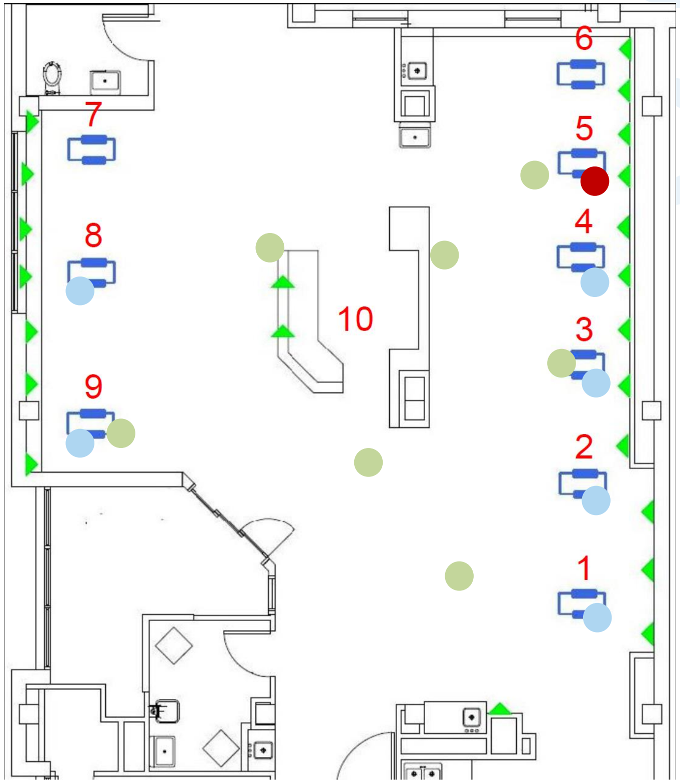
Simulating the spread of MRSA in the dialysis unit

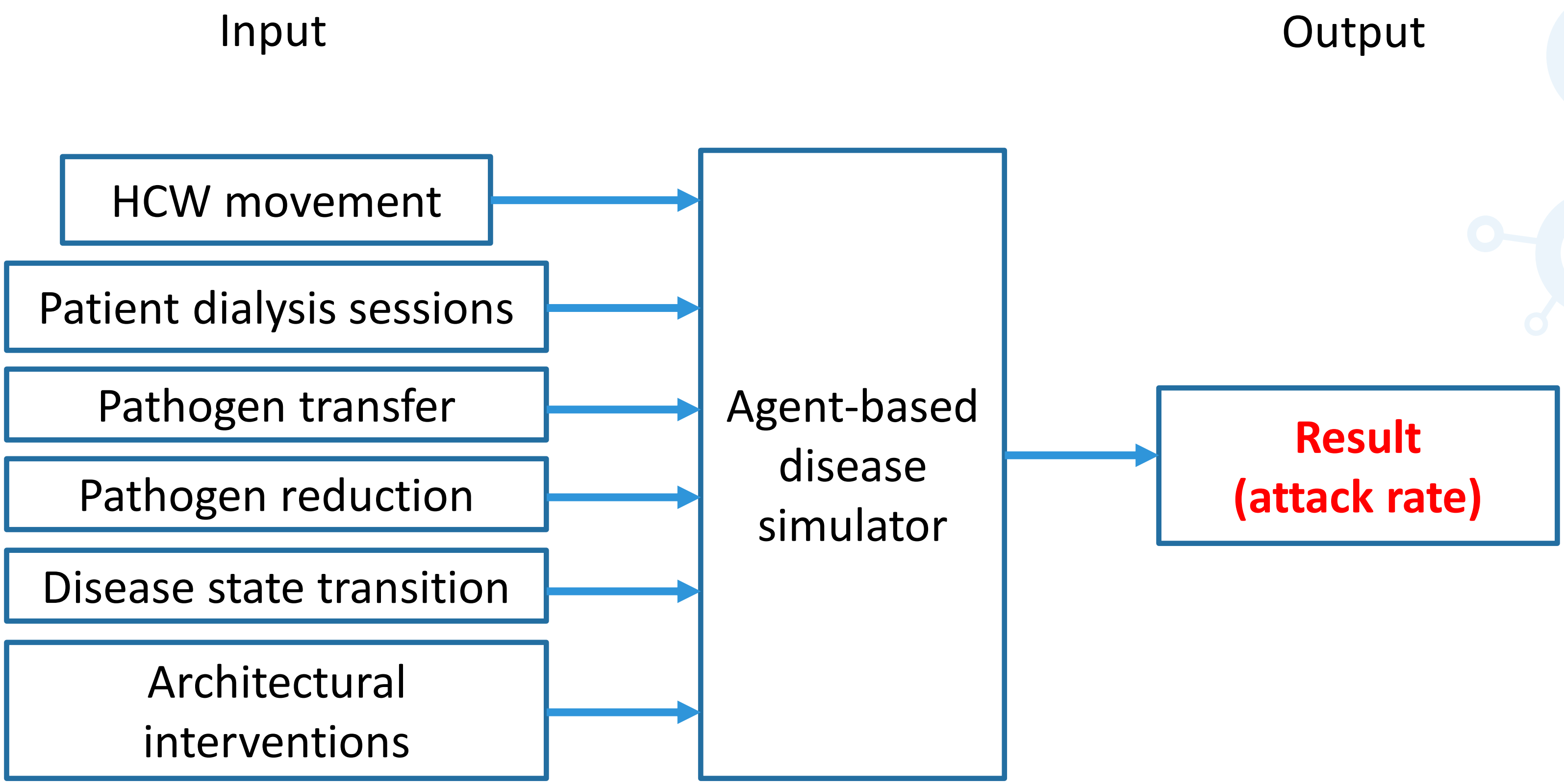
Patient scheduling & disease model

- Simulation runs for 30 days (1,000 replicates)
  - Interactions of HCWs and patients of one day is replayed
  - Patients dialyze 3 times per week
    - Monday-Wednesday-Friday: 20 patients
    - Tuesday-Thursday-Saturday: 20 patients
- Day1, morning, one patient gets infected
  - Patients adhere to SIS model
    - Infection duration: 10 days
  - HCWs become colonized but never become infected



H. W. Hethcote, "The mathematics of infectious diseases," SIAM Rev., vol.42, no.4, pp.599–653, Dec.2000.
2019 MRSA Research Center, The University of Chicago, "Frequently asked questions about MRSA," http://mrsa-research-center.bsd.uchicago.edu/patients_families/faq.html

Overview


Input
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Results

Baseline simulation result

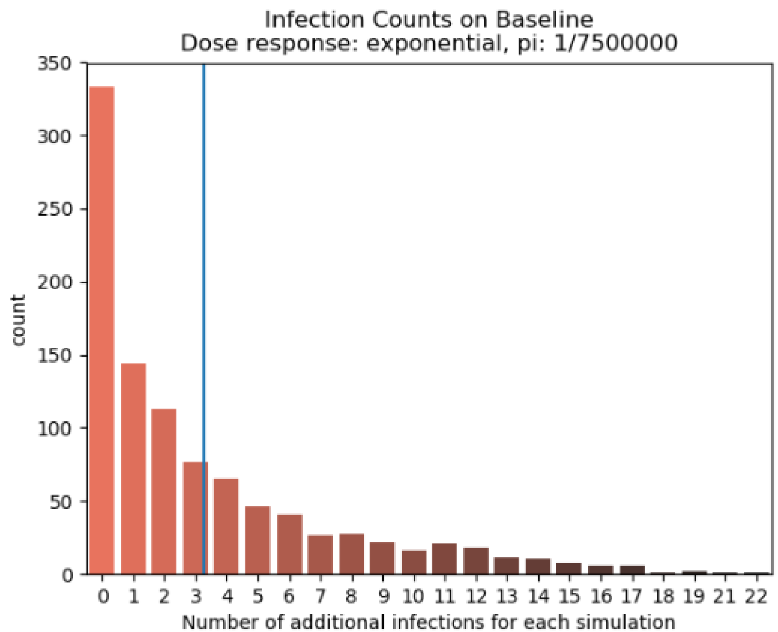
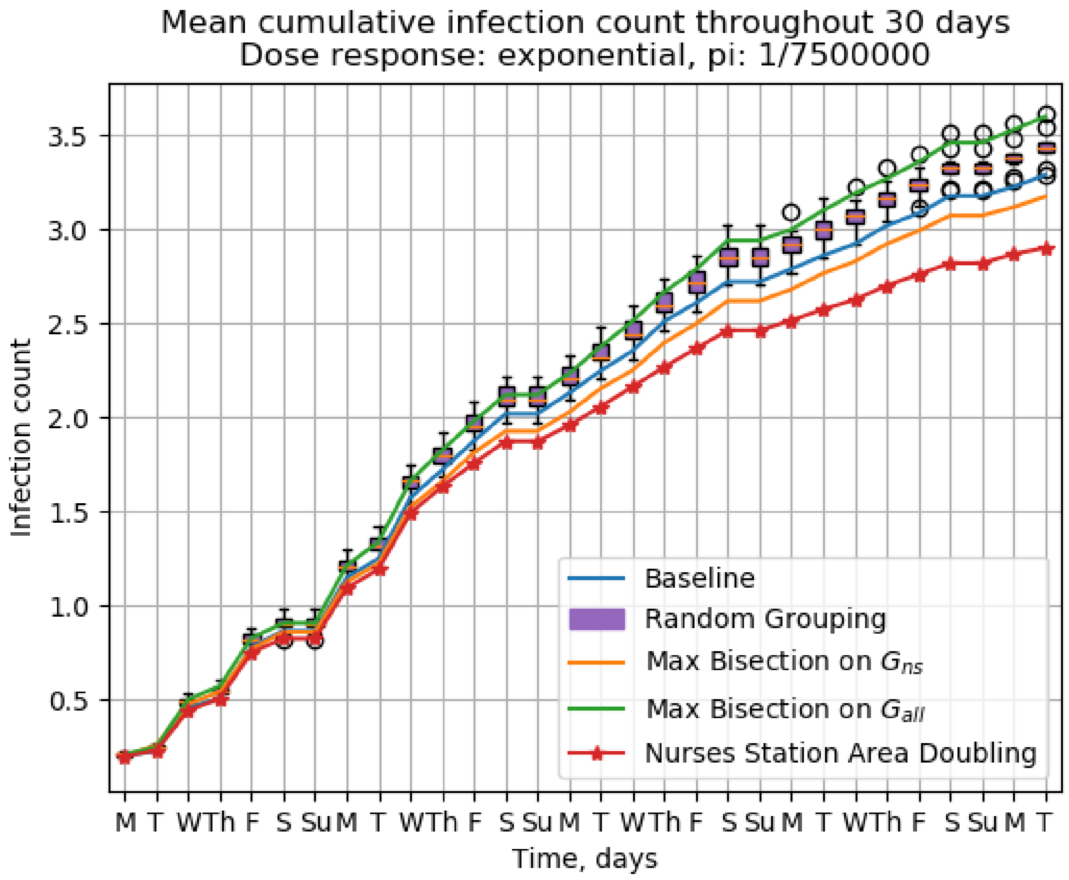


Fig. 4. **Distribution of infection counts in 1000 repetitions of the baseline simulation using the model parameters in Table III.** The mean and median infection counts on the baseline simulation are 3.287 and 2, respectively with a std. dev. of 4.129. The mean infection count is depicted as a vertical line.

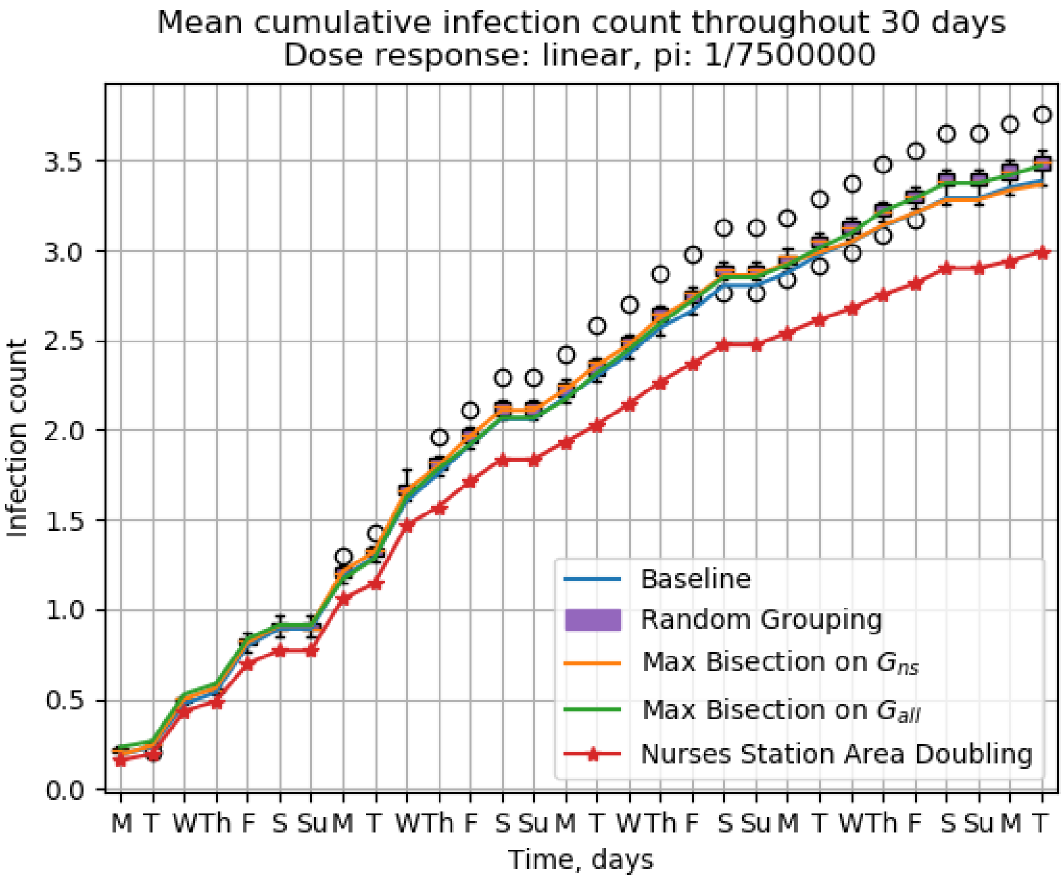
Results

Cumulative infection counts (Fig. 5a)



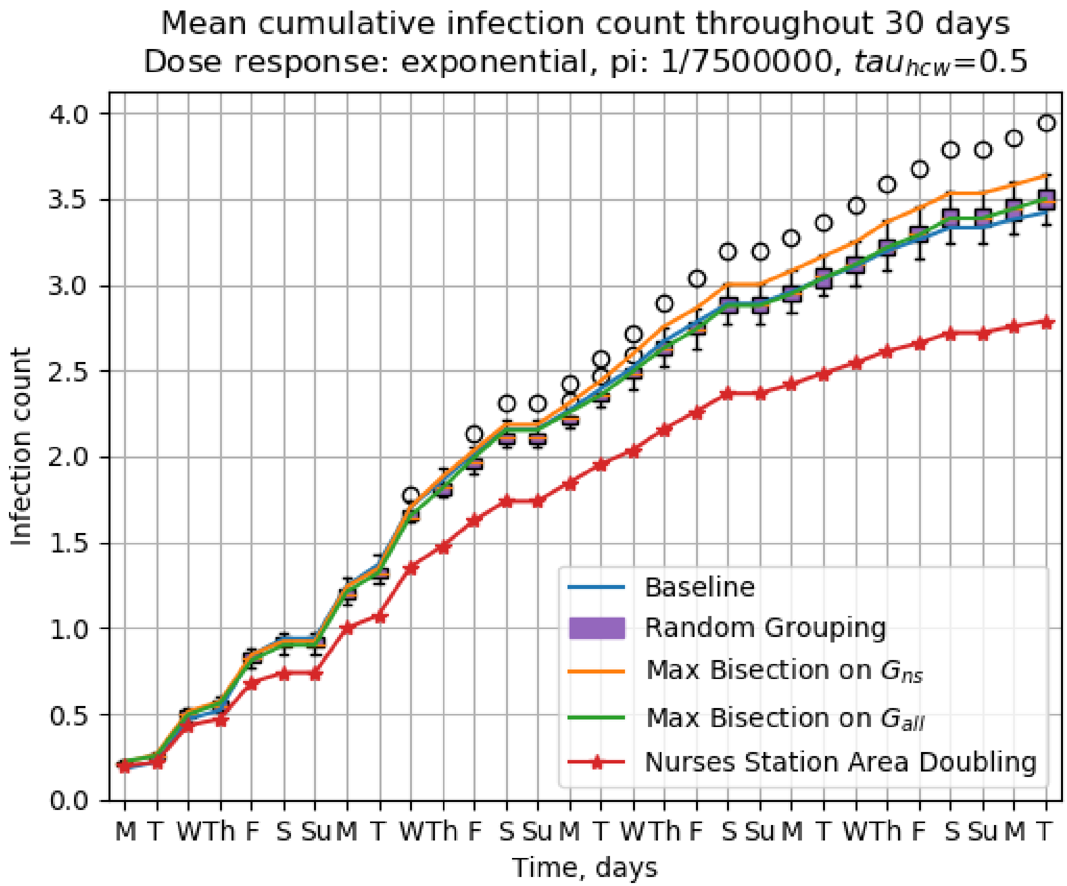
Results

Cumulative infection counts (Fig. 5b)



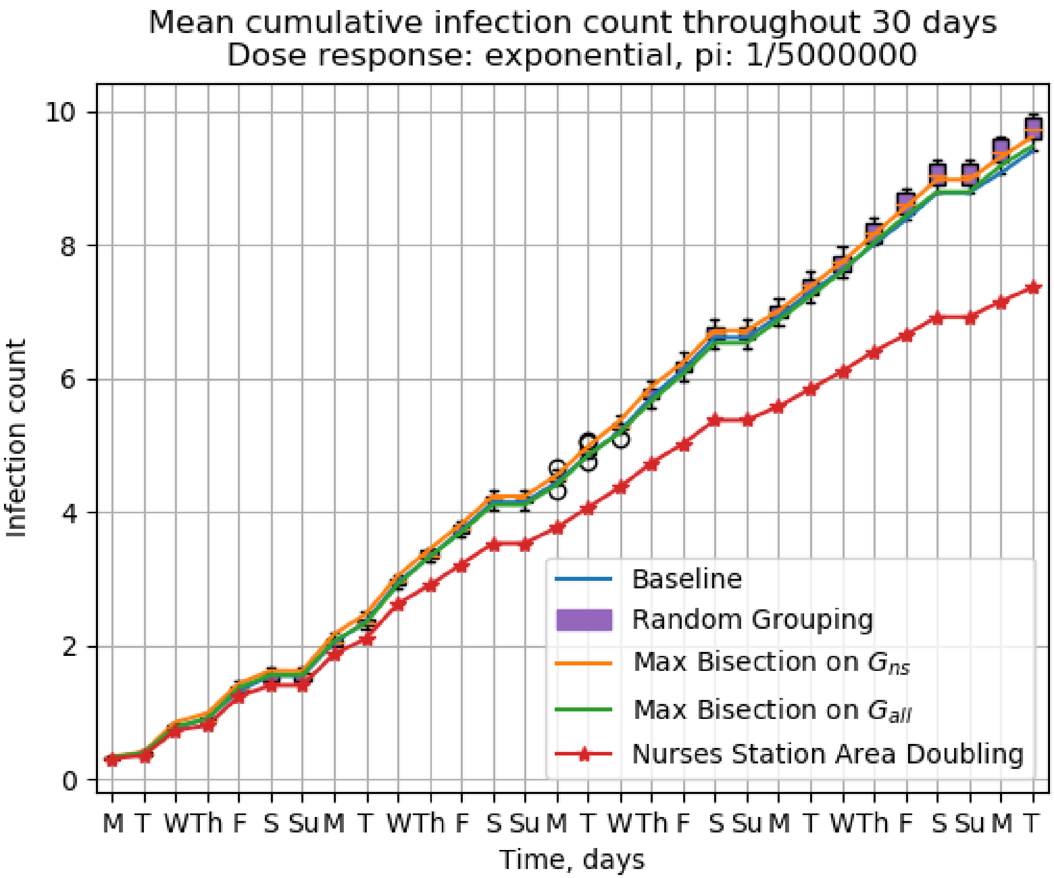
Results

Cumulative infection counts (Fig. 5c)



Results

Cumulative infection counts (Fig. 5d)



Results

Percentage changes in cumulative infection counts

TABLE V
PERCENTAGE CHANGES IN MEAN INFECTION COUNTS OF DIFFERENT POLICIES[a]

Parameters	*Policy1*	*Policy2*	*Policy3*	*Policy4*
Baseline (Fig. 5a)	1%	-3%	9%	**-12%**
$f(x) = linear$ (Fig. 5b)	11%	-1%	3%	**-12%**
$\tau_{hcw} = 0.5$ (Fig. 5c)	7%	6%	2%	**-19%**
$\pi = \frac{1}{5M}$ (Fig. 5d)	4%	2%	1%	**-22%**

[a]Percentage changes are relative to that of *Policy0*.

Results

Key takeaways

- Reducing HCW-HCW contacts could actually lead to an increase in infections
  - Very different from standard disease diffusion models
  - Little is known about the impact of the environment on disease spread
  - Caution against the unintended consequences of reducing HCW interactions
- Doubling the surface area of the nurses' station substantially reduces infection counts
  - Dilution is the key to reduce spread of MRSA!

David Kempe, Jon Kleinberg, and Éva Tardos. 2003. Maximizing the spread of influence through a social network. In Proceedings of the ninth ACM SIGKDD international conference on Knowledge discovery and data mining (KDD '03). ACM, New York, NY, USA, 137-146

Questions?

https://vinci.cs.uiowa.edu/compepi/wp-content/papercite-data/pdf/jang19.pdf