Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Department of Information Technology
and Electrical Engineering

Performance of Distributed Algorithms in DTNs

Towards an Analytical Framework for Heterogeneous Mobility

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Outline

Two Key Points

Two Key Points

Greedy (combinatorial) optimization

Two Key Points

Greedy (combinatorial) optimization

Heterogeneous mobility

Greed Is Not a Sin in DTNs

Sporadic, partial connectivity

⇓

Highly dynamic graph

⇓

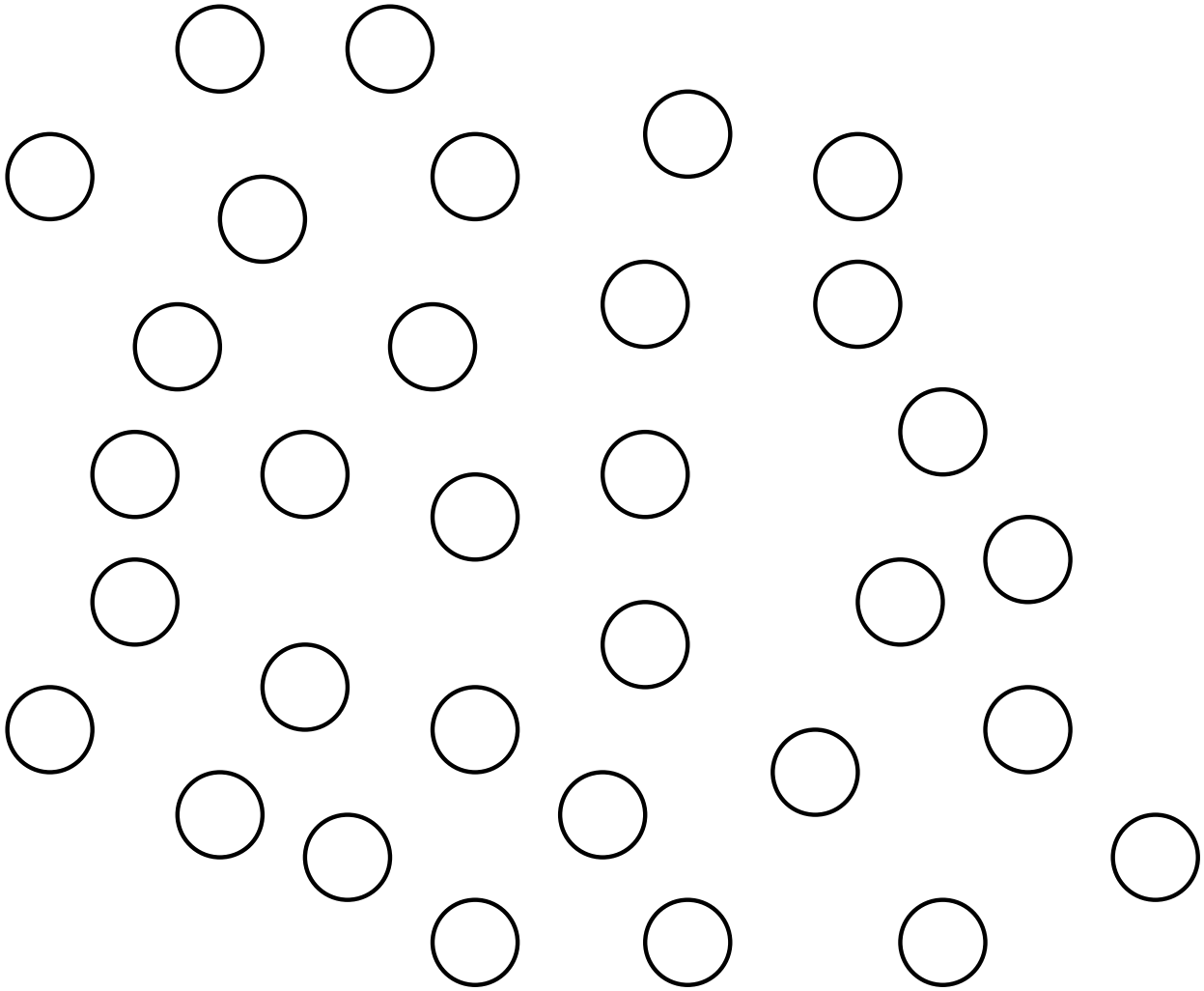
Greedy algorithms for everything

This present contact

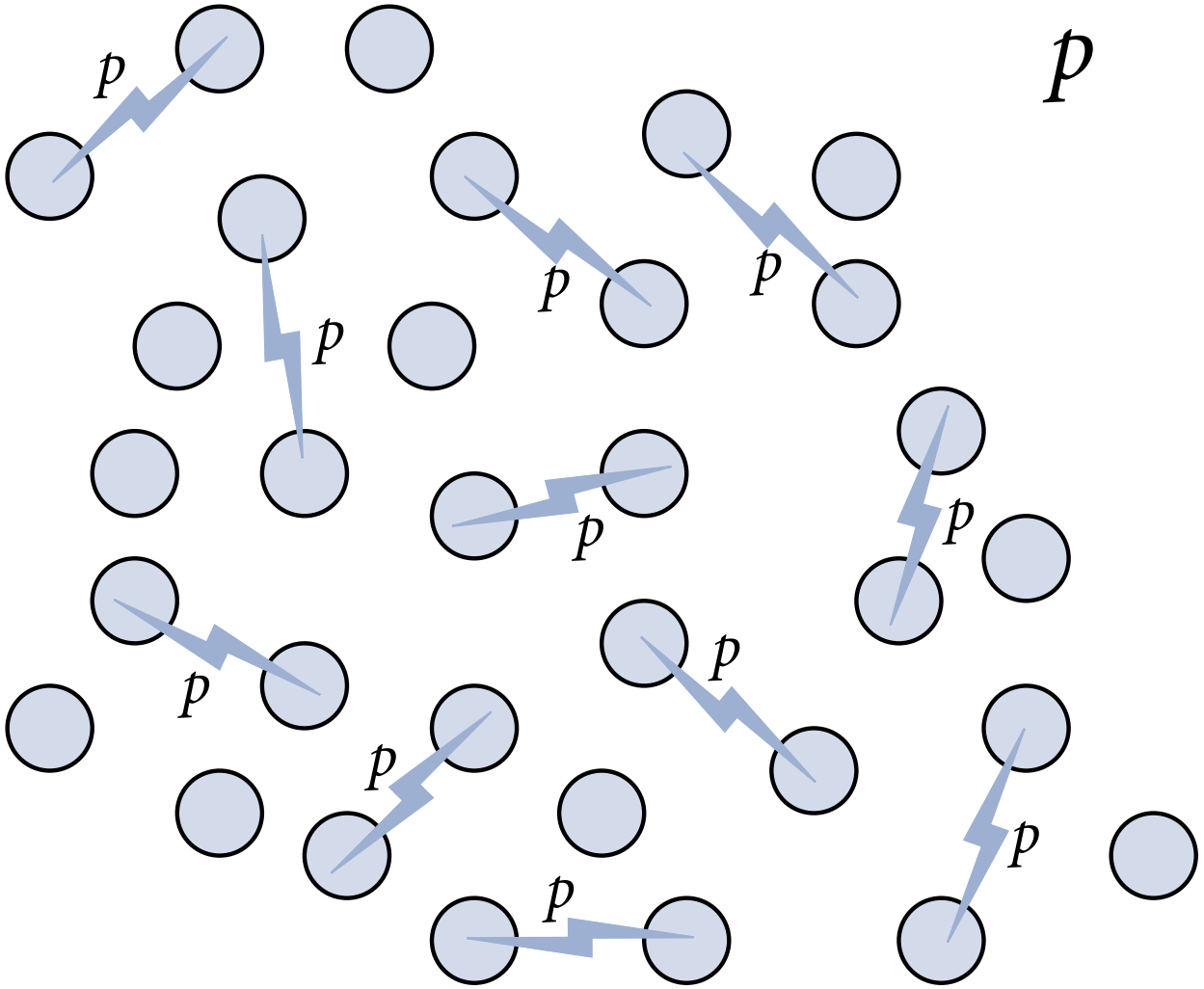
Potential future contacts

*Proverb: A bird in hand is worth two in the bush.

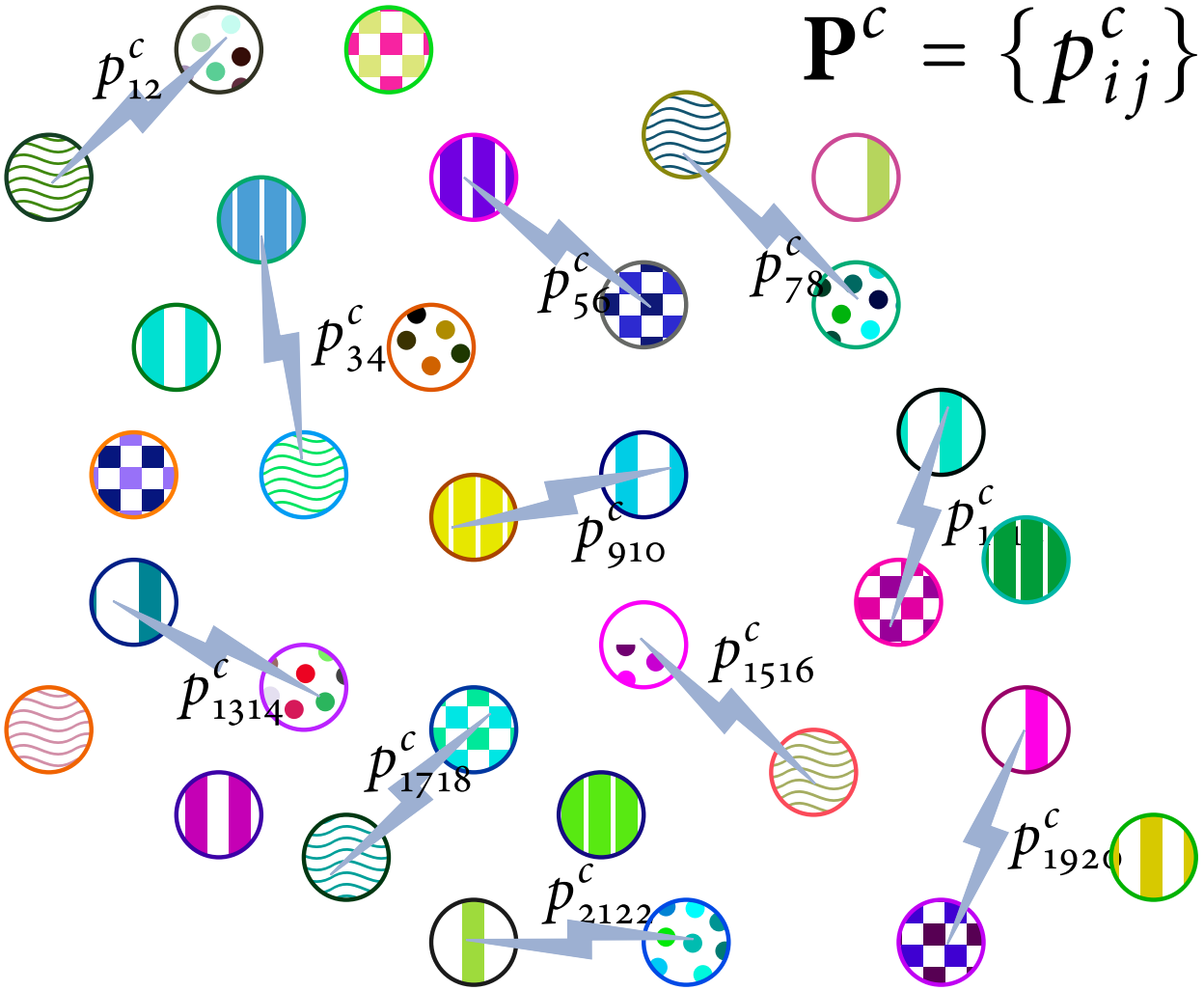
Current DTN Analytical Models



Current DTN Analytical Models



Studies of Real Mobility



Using Real Mobility

New Algorithms/Protocols (still greedy)

E. Daly and M. Haahr
Social network analysis for routing in disconnected delay-tolerant MANETs
MobiHoc 2007

P. Hui, J. Crowcroft and E. Yoneki
BubbleRap: Social-based Forwarding in Delay Tolerant Networks
MobiHoc 2008

Models (still individual)

T. Spyropoulos, T. Turletti and K. Obraczka
Routing in Delay-Tolerant Networks Comprising Heterogeneous Node Populations
TMC 2009

Unified Analysis for Optimization in DTNs

Decouple

- **mobility** (contact probability matrix $\mathbf{P}^c_{ij}$)
- **algorithms** (most of the time greedy)

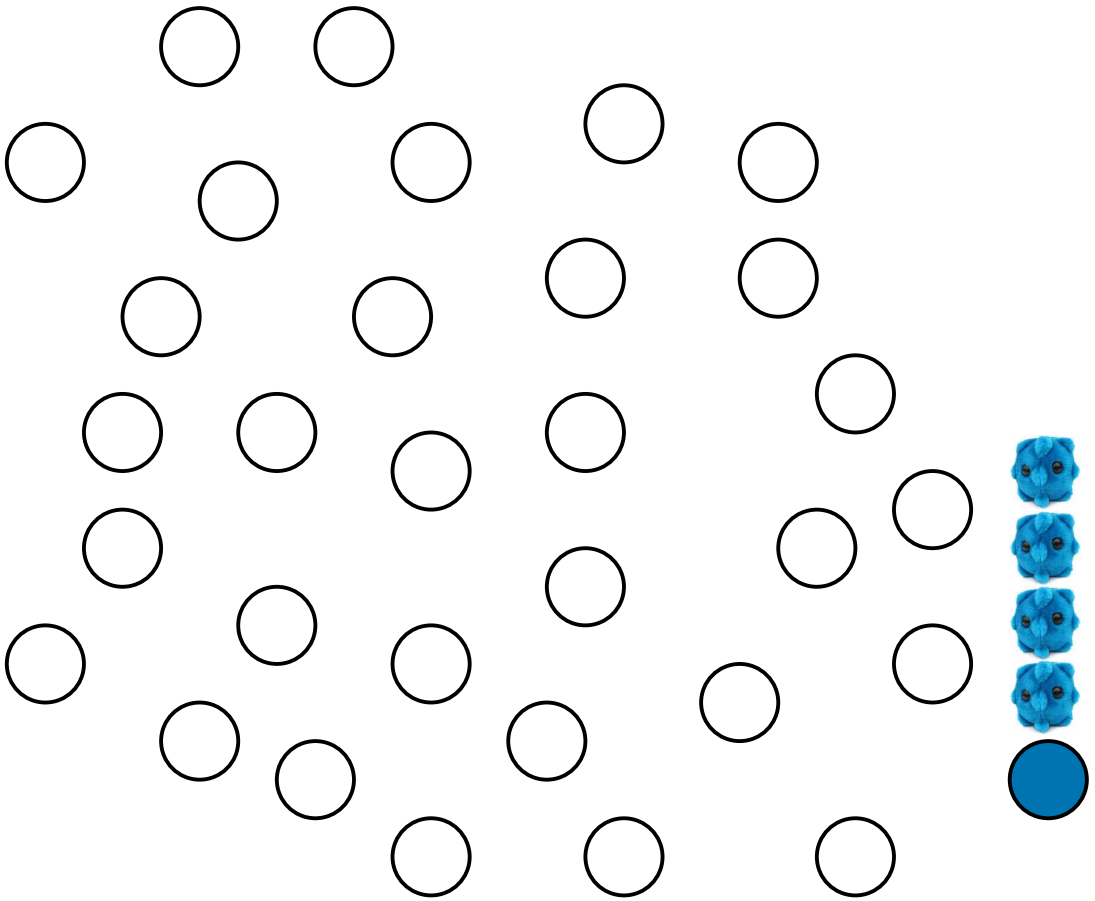
to obtain

$\Rightarrow$ correctness conditions on mobility scenario

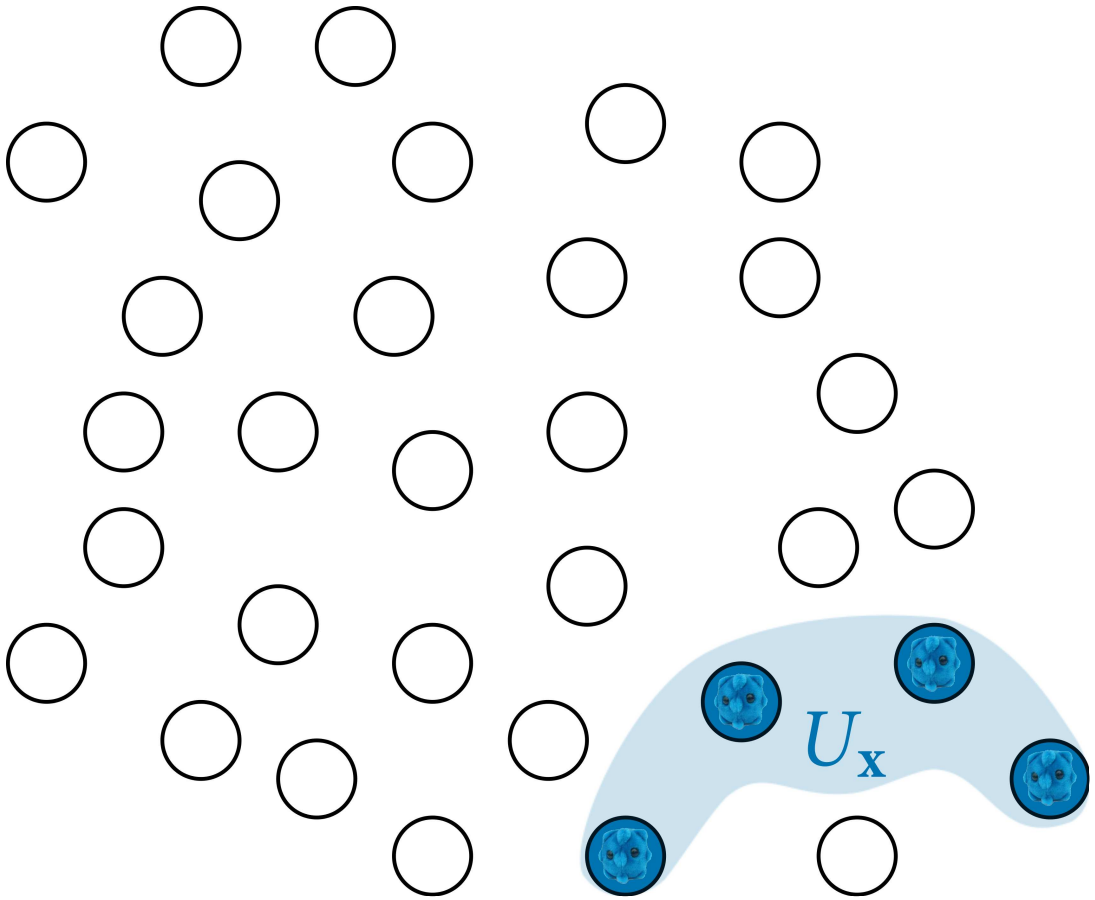
$\Rightarrow$ convergence probability and convergence delay

Illustrative example: Content Placement

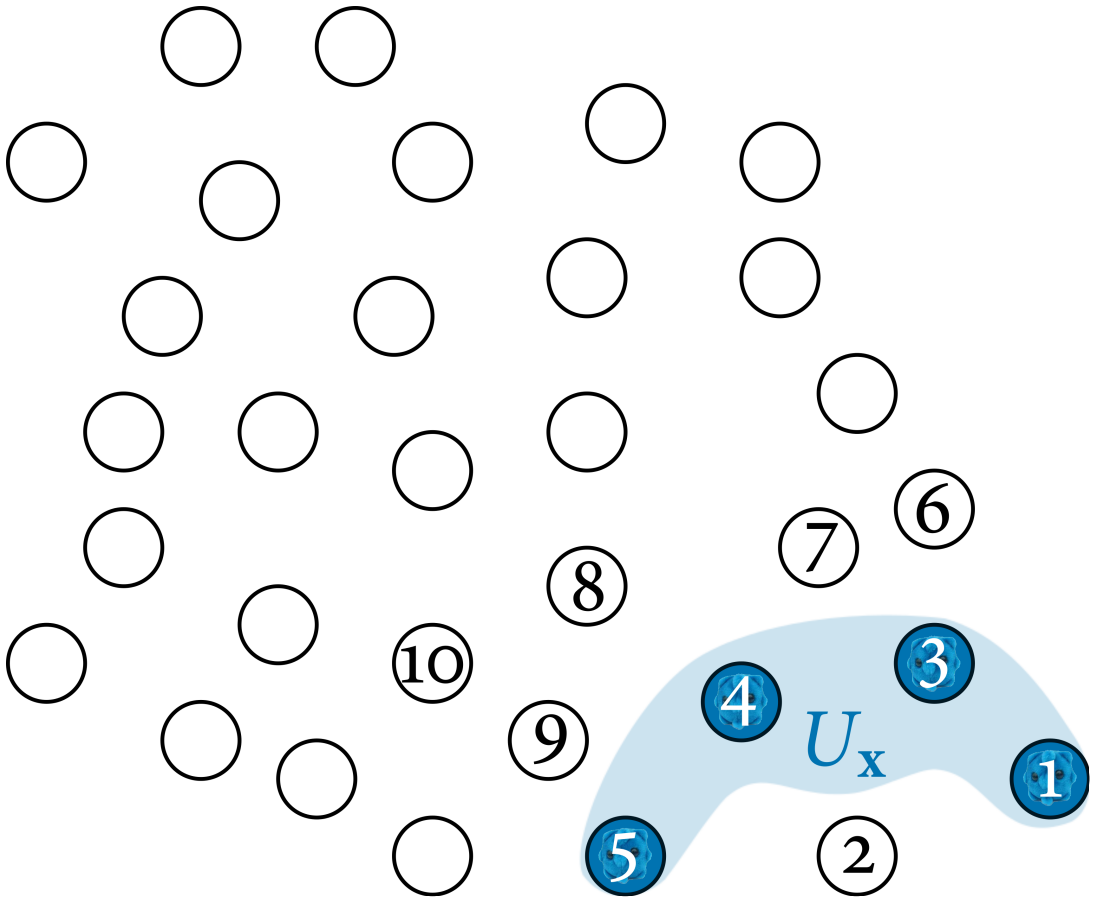
Content/service placement



Content/service placement

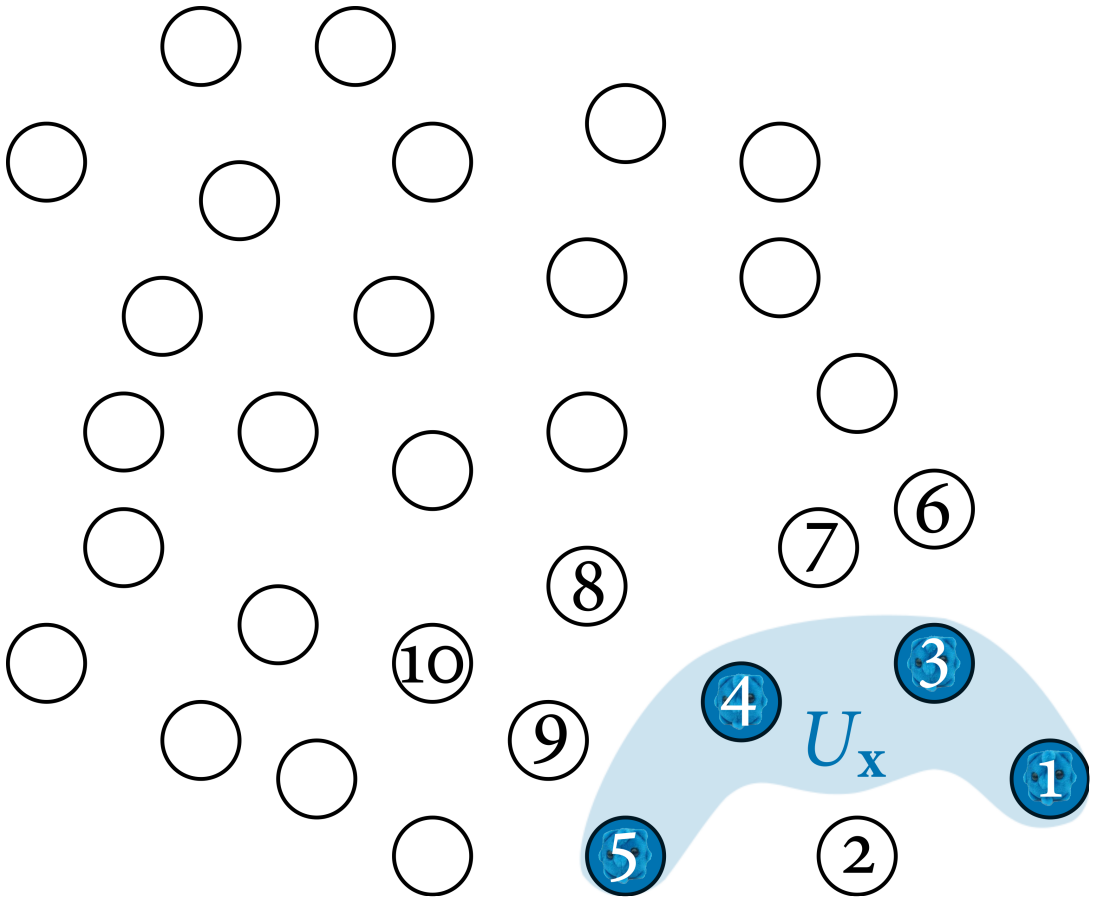


Content/service placement



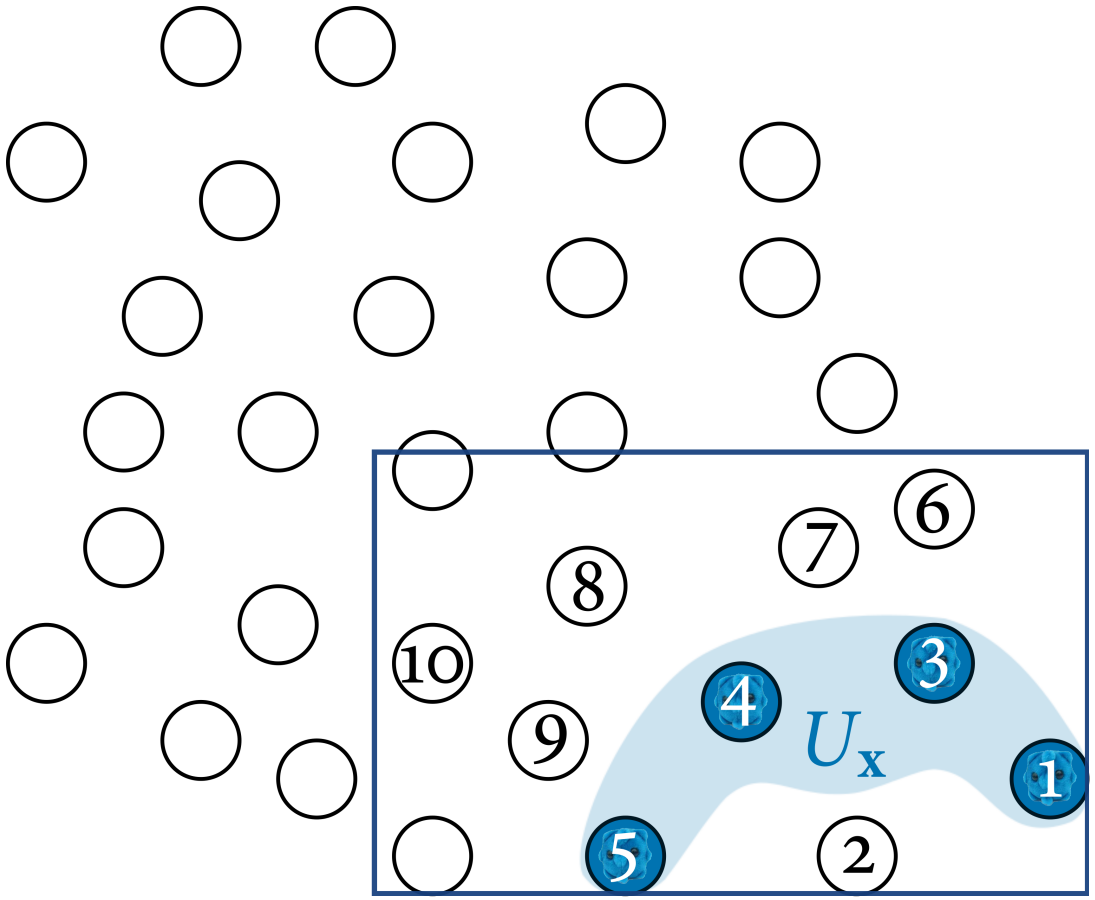
$$\mathbf{x} = (x_1, x_2, \ldots, x_N) = (1, 0, 1, 1, 1, 0, \ldots, 0)$$

Content/service placement



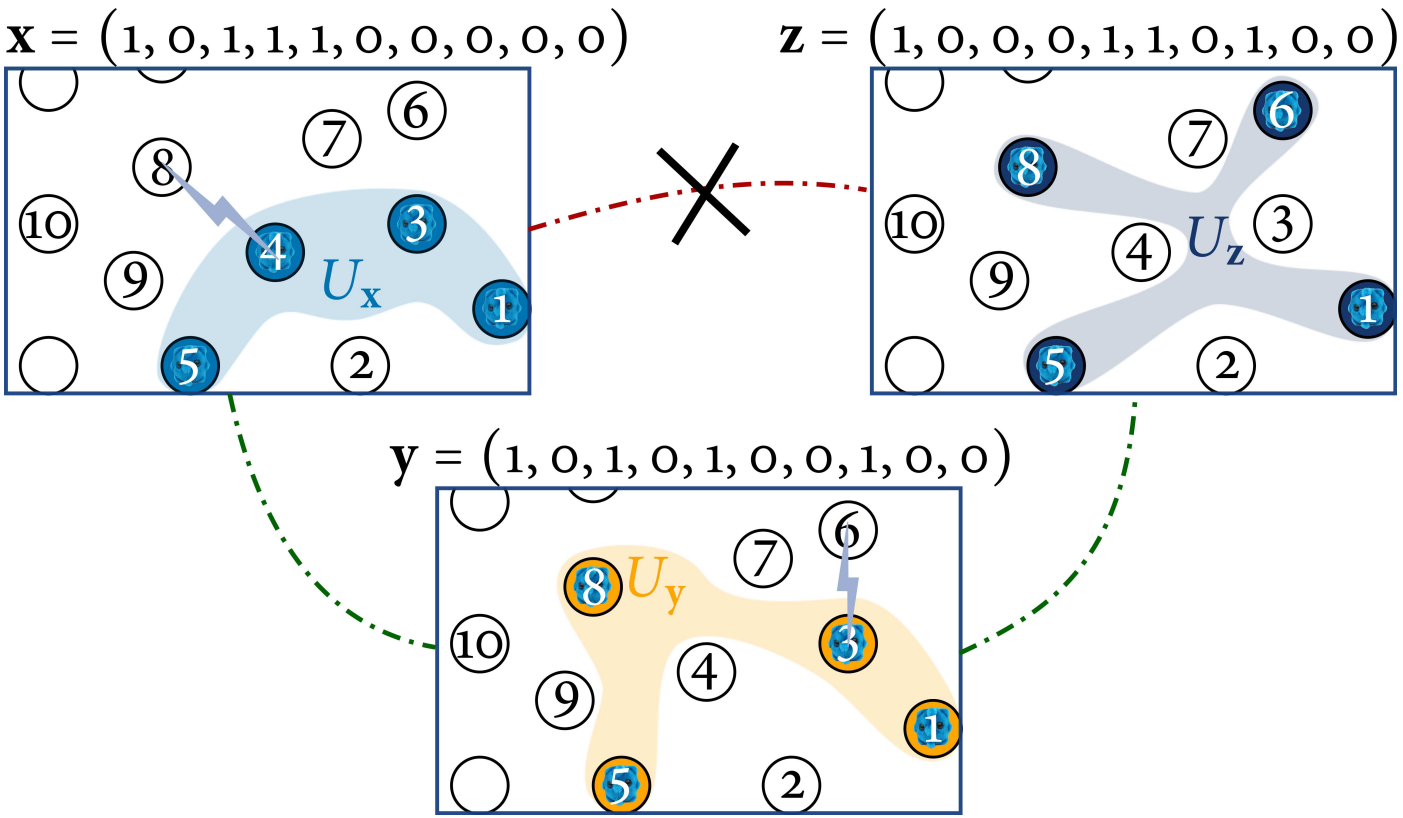
Node state space: $\{0, 1\}$ Network state space: $\binom{N}{L}$

Content/service placement

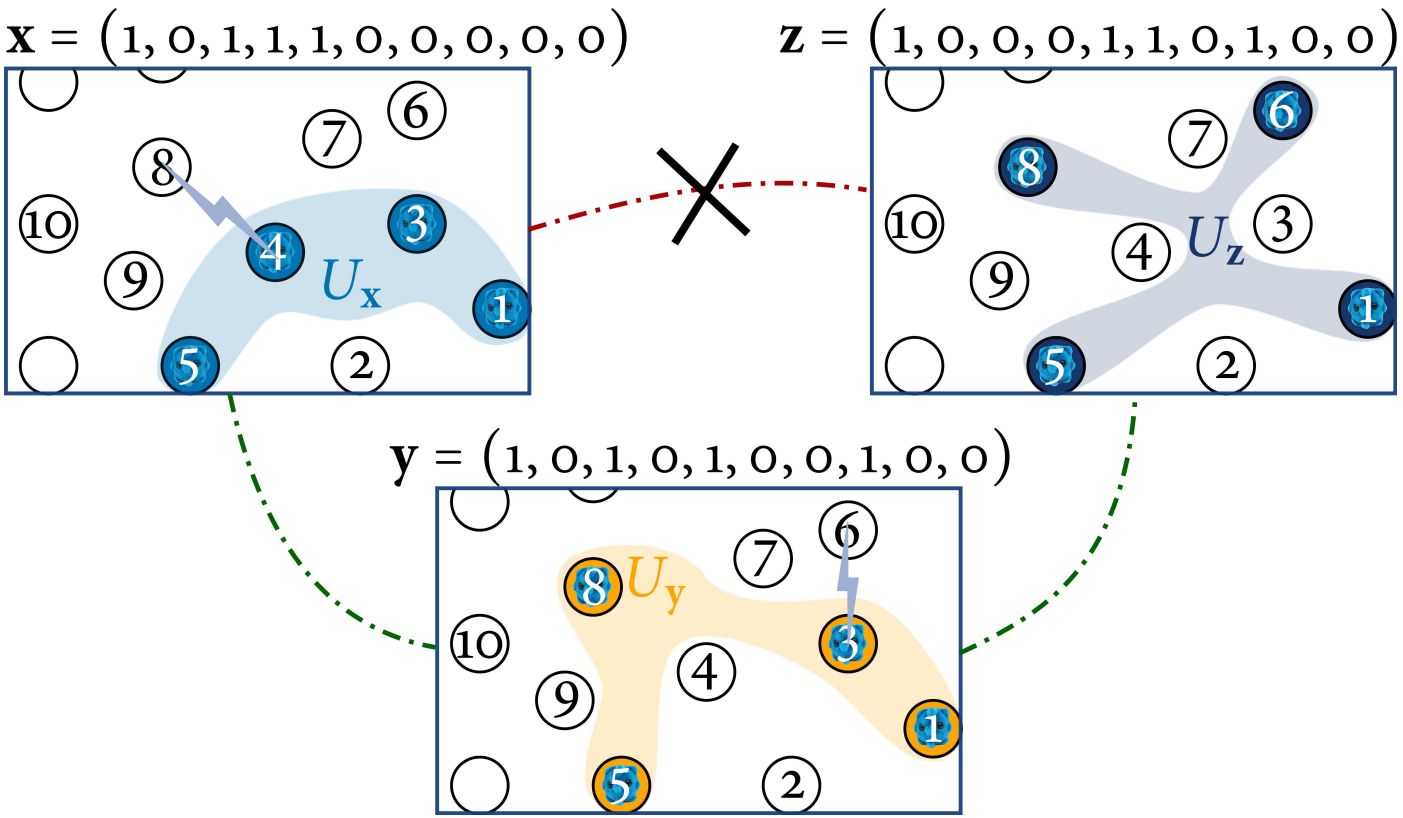


Node state space: $\{0, 1\}$ Network state space: $\binom{N}{L}$

Network State Difference

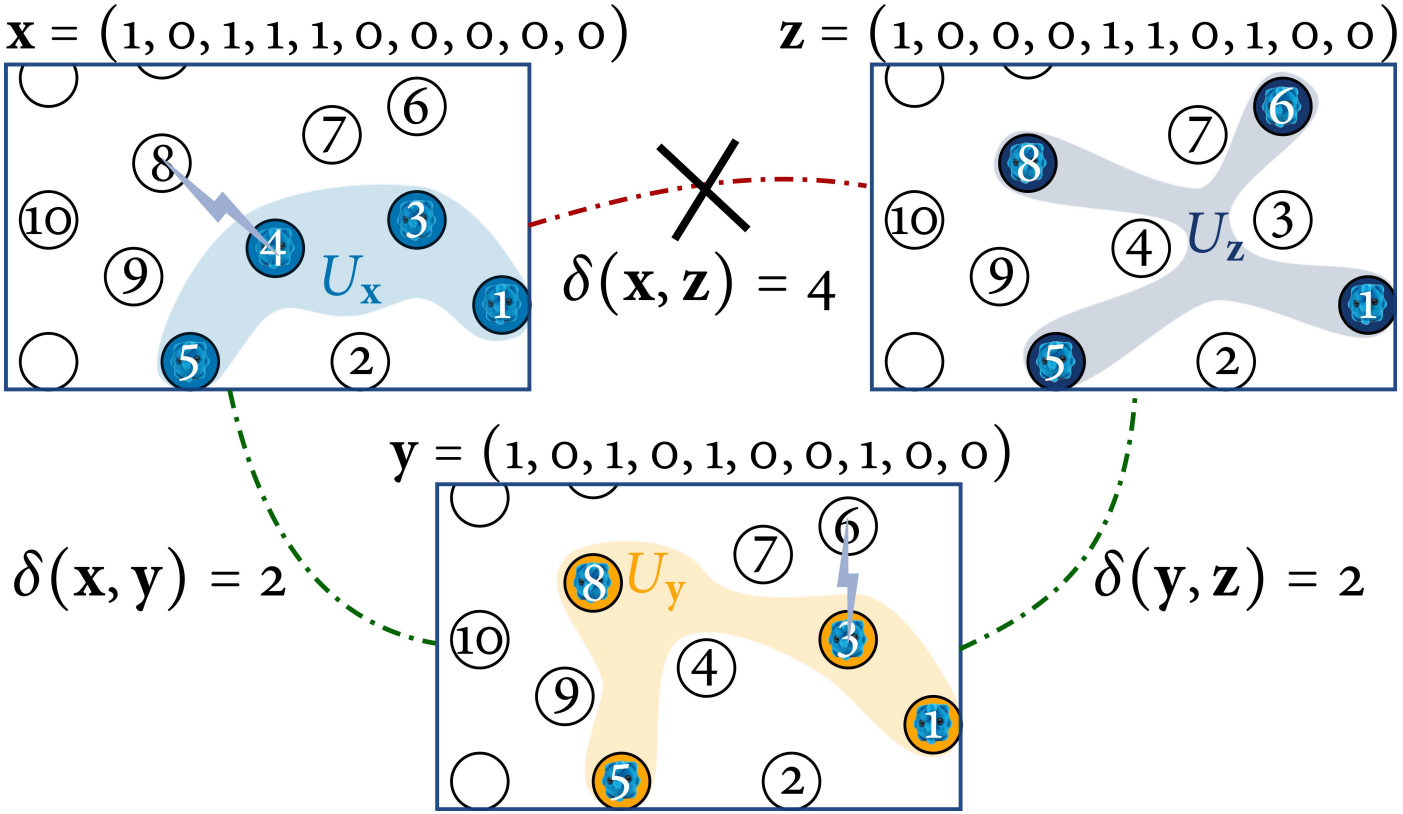


Network State Difference



$$\delta(\mathbf{x}, \mathbf{y}) = \sum_{1 \leqslant i \leqslant N} \mathbb{1}\{x_i \neq y_i\}$$

Network State Difference

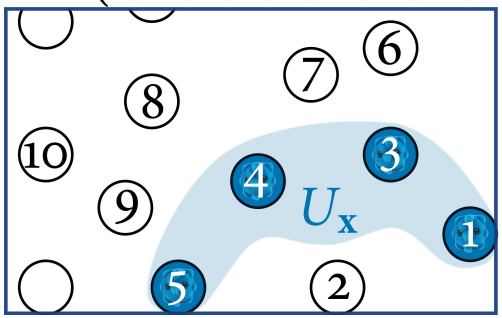


$$\delta(\mathbf{x}, \mathbf{y}) = \sum_{1 \leqslant i \leqslant N} \mathbb{1}\{x_i \neq y_i\}$$

Local Optimization Algorithms

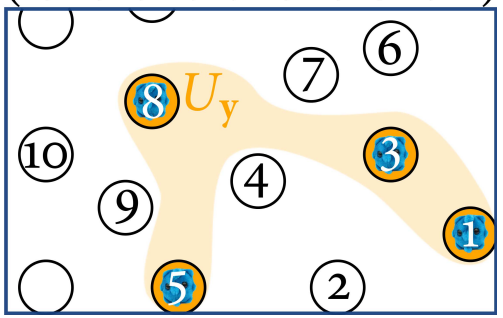
Let $U_{\mathbf{x}} > U_{\mathbf{y}}$:

$\mathbf{x} = (1, 0, 1, 1, 1, 0, 0, 0, 0, 0)$



$p_{\mathbf{xy}} =$

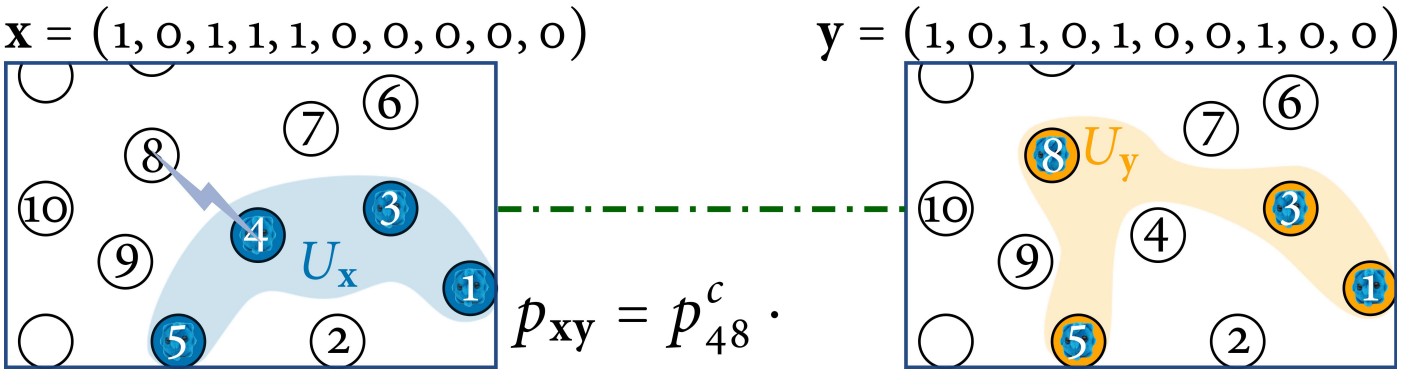
$\mathbf{y} = (1, 0, 1, 0, 1, 0, 0, 1, 0, 0)$



Transition probability $p_{\mathbf{xy}}$:

Local Optimization Algorithms

Let $U_{\mathbf{x}} > U_{\mathbf{y}}$:

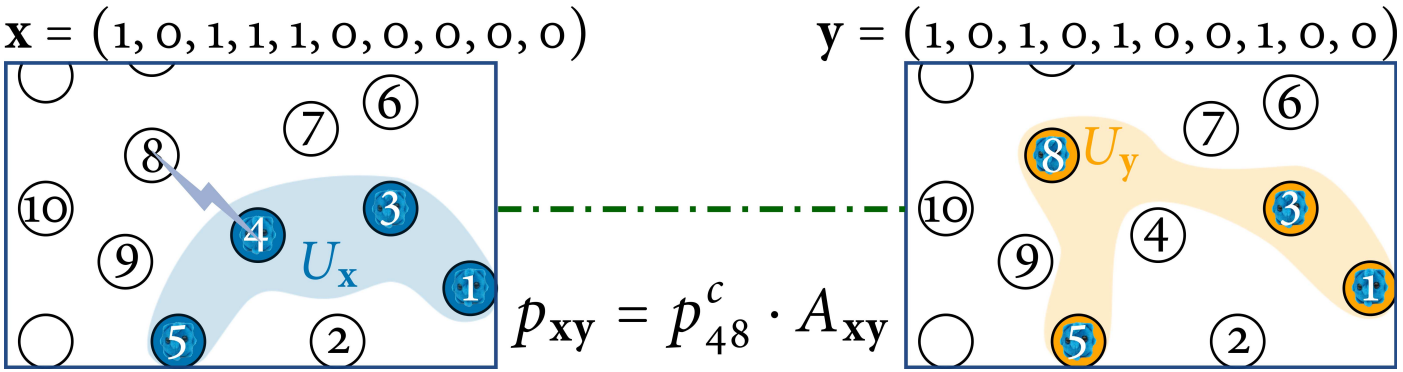


Transition probability $p_{\mathbf{xy}}$:

1. contact probability p^c_{ij}

Local Optimization Algorithms

Let $U_{\mathbf{x}} > U_{\mathbf{y}}$:



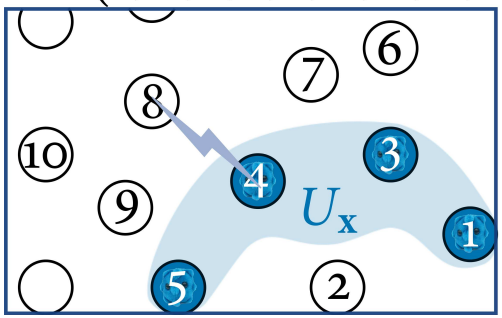
Transition probability $p_{\mathbf{xy}}$:

1. contact probability p^c_{ij}
2. acceptance probability $A_{\mathbf{xy}} = 0$

Local Optimization Algorithms

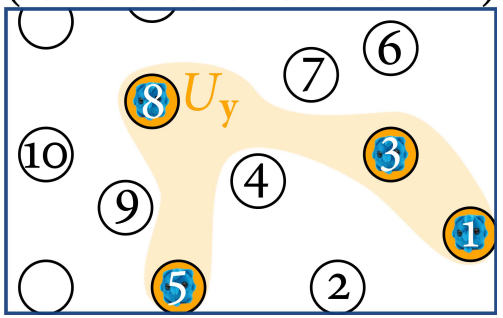
Let $U_{\mathbf{x}} > U_{\mathbf{y}}$:

$\mathbf{x} = (1, 0, 1, 1, 1, 0, 0, 0, 0, 0)$



$p_{\mathbf{xy}} = p^c_{48} \cdot 0$

$\mathbf{y} = (1, 0, 1, 0, 1, 0, 0, 1, 0, 0)$



Transition probability $p_{\mathbf{xy}}$:

1. contact probability $\quad p^c_{ij}$
2. acceptance probability $\quad A_{\mathbf{xy}} = 0$

$A_{\mathbf{xy}} = \mathbb{1}\{U_{\mathbf{x}} < U_{\mathbf{y}}\}$ (greedy)

$A_{\mathbf{xy}} = f(U_{\mathbf{x}}, U_{\mathbf{y}})$ (probabilistic)

Utilities

- node mobility ⇒ degree, contact probability
- node features ⇒ buffer space, battery
- content ⇒ demand for content

Content Placement

- node utility: $U \propto$ node degree
- state utility: sum of individual utilities

A. Picu and T. Spyropoulos
*Minimum Expected *-cast Time in DTNs*
BIONETICS 2009

Putting the pieces together

Pieces of our new model:

1. Mobility (heterogeneous) $\Rightarrow$ contact probability matrix $\mathbf{P}^c = \{p_{ij}^c\}$
2. *Solution space (node & network)* $\Rightarrow$ *e.g., combinations of L nodes*
3. *Utilities* $\Rightarrow$ *e.g., node degree*
4. Algorithm $\Rightarrow$ acceptance probability matrix $\mathbf{A} = \{A_{\mathbf{xy}}\}$

The Markov Chain

Complicated problem $\Rightarrow$ Transition matrix, $\mathbf{P} = \{p_{\mathbf{xy}}\}$

$$\underset{\mathbf{P}^C}{\text{mobility}} \circ \underset{\mathbf{A}}{\text{algorithm}}$$

$$\mathbf{P}^C = \begin{bmatrix} 0 & p^c_{12} & \cdots & p^c_{1N} \\ p^c_{21} & 0 & \cdots & p^c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p^c_{N1} & \cdots & \cdots & 0 \end{bmatrix} \circ \mathbf{A} = \begin{bmatrix} 1 & A_{\mathbf{x_1x_2}} & \cdots & A_{\mathbf{x_1x_M}} \\ A_{\mathbf{x_2x_1}} & 1 & \cdots & A_{\mathbf{x_2x_M}} \\ \vdots & \vdots & \ddots & \vdots \\ A_{\mathbf{x_Mx_1}} & \cdots & \cdots & 1 \end{bmatrix}$$

The Markov Chain

Complicated problem $\Rightarrow$ Transition matrix, $\mathbf{P} = \{p_{\mathbf{xy}}\}$

$$\mathbf{P} = \begin{bmatrix} p_{\mathbf{x}_1\mathbf{x}_1} & p_{\mathbf{x}_1\mathbf{x}_2} & \cdots & p_{\mathbf{x}_1\mathbf{x}_M} \\ p_{\mathbf{x}_2\mathbf{x}_1} & p_{\mathbf{x}_2\mathbf{x}_2} & \cdots & p_{\mathbf{x}_2\mathbf{x}_M} \\ \vdots & \vdots & \ddots & \vdots \\ p_{\mathbf{x}_M\mathbf{x}_1} & \cdots & \cdots & p_{\mathbf{x}_M\mathbf{x}_M} \end{bmatrix}$$

$$\boxed{\mathbf{P} = \{p_{\mathbf{xy}}\} = p_{ij}^{c} \cdot A_{\mathbf{xy}}}$$

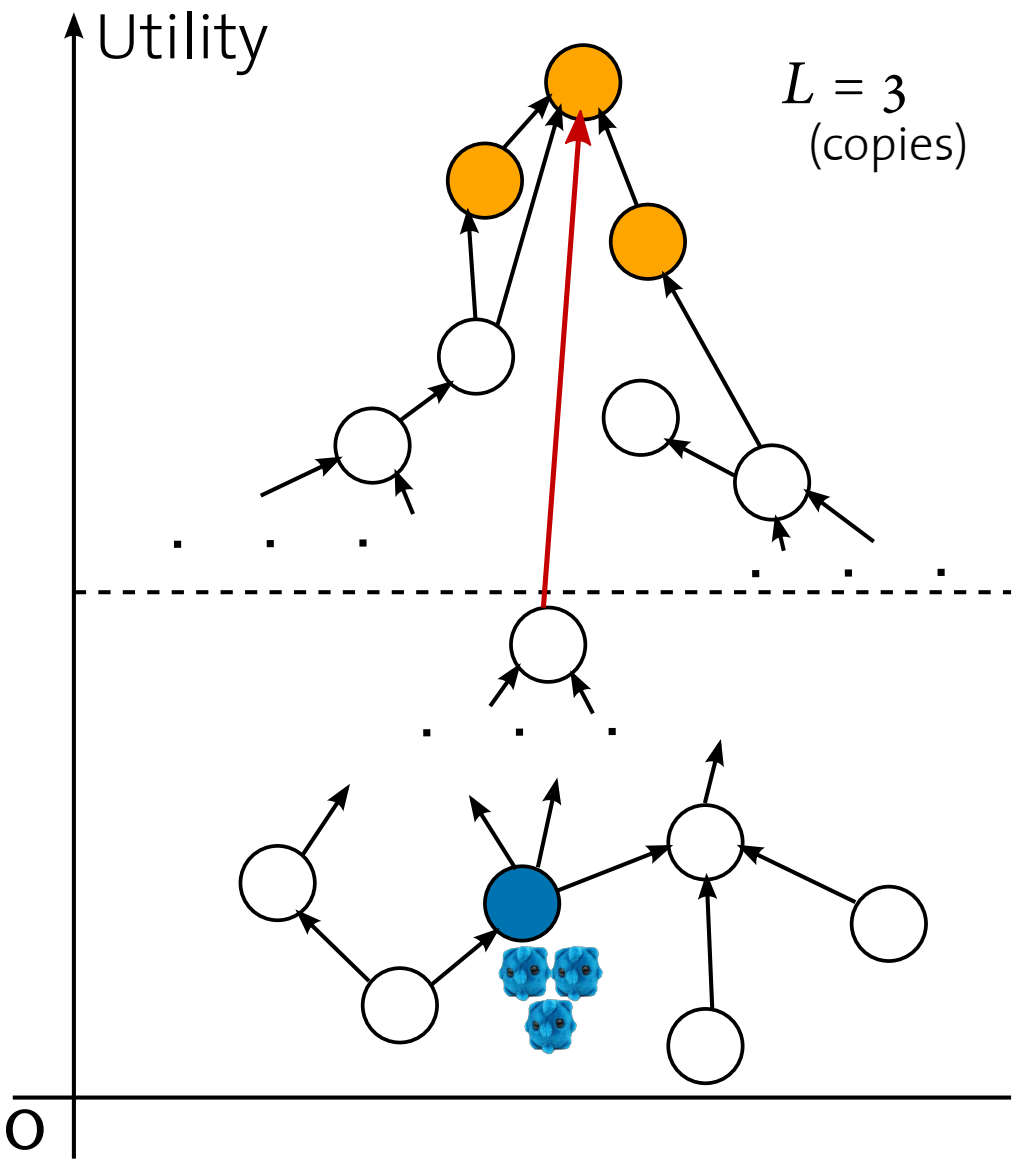
Why Is This Useful?

- Correctness analysis
  - Feasability of (mobility + algorithm)
- Convergence analysis
  - Achieve trade-off (e.g., delay vs. # copies)
  - Tune parameters
  - Assess performance

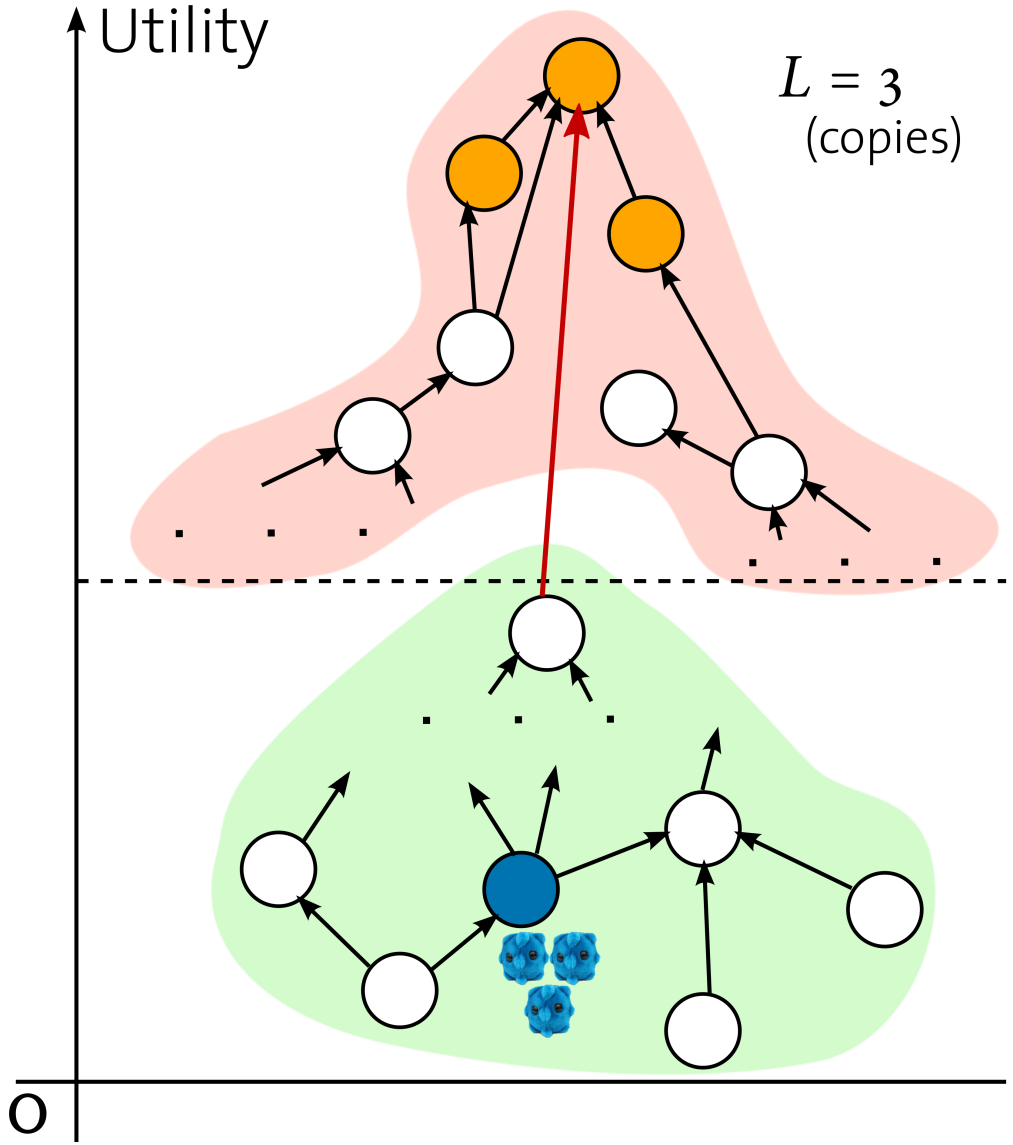
When Is Greedy Content Placement Correct?

Every node has at least one higher utility neighbor?

When Is Greedy Content Placement Correct?



When Is Greedy Content Placement Correct?

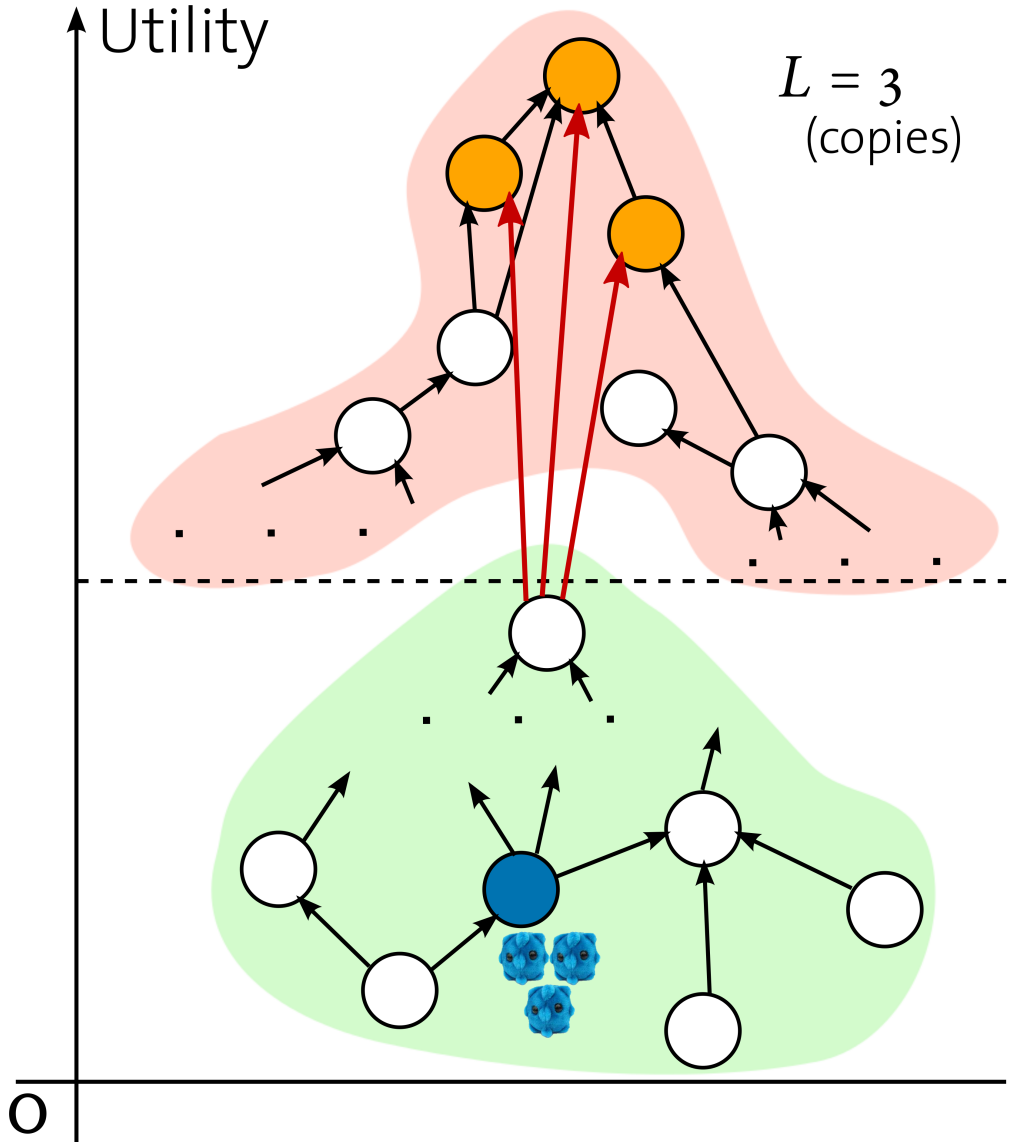


When Is Greedy Content Placement Correct?

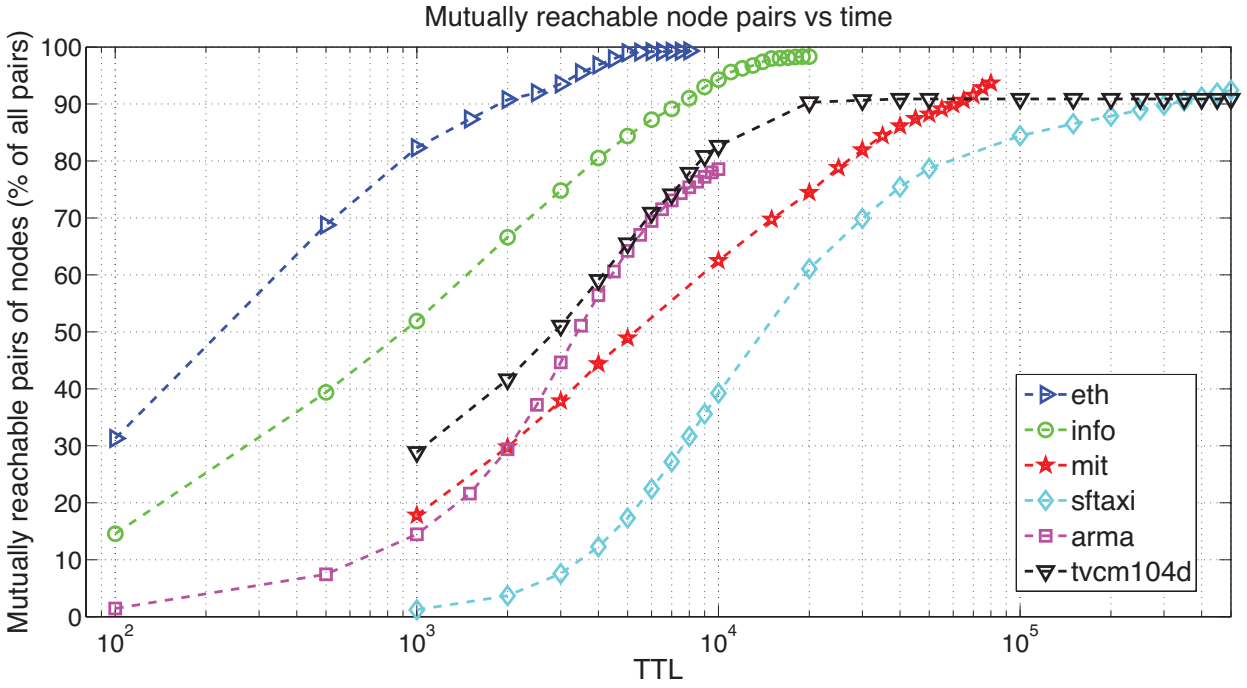
L

Every node has at least ~~one~~ higher utility neighbor**s**?

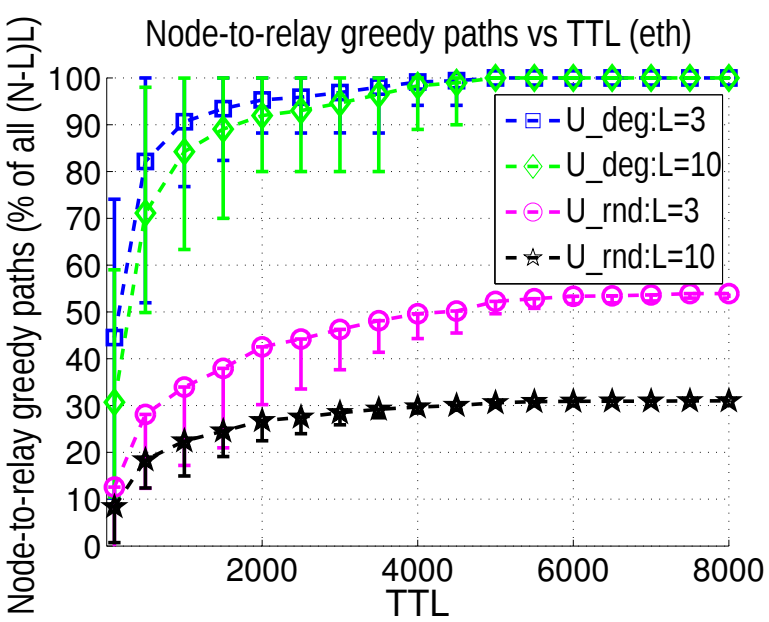
When Is Greedy Content Placement Correct?

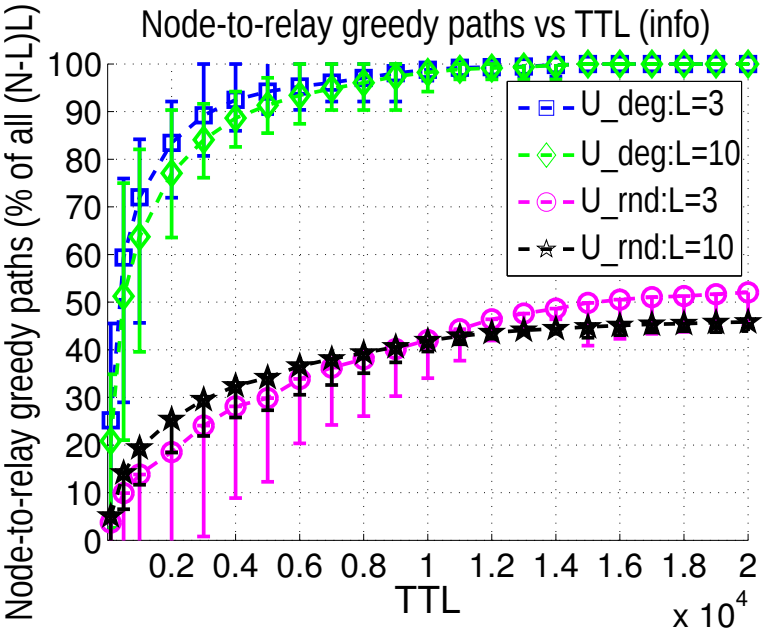


Multihop greedy paths in traces



Impact of L and utility





What about convergence?

Correct Algorithm

- ⇒ Convergence probability = 1!
- ⇒ Convergence delay = ?

Non-correct Algorithm

- ⇒ Convergence probability = ?
- ⇒ Convergence delay = ?

Recall Our *Absorbing* Markov Chain

Complicated problem $\Rightarrow$ Transition matrix, $\mathbf{P} = \{p_{\mathbf{xy}}\}$

$$\underbrace{\mathbf{P}^C}_{\text{mobility}} \circ \underbrace{\mathbf{A}}_{\text{algorithm}}$$

$$\mathbf{P}^C = \begin{bmatrix} 0 & p^C_{12} & \cdots & p^C_{1N} \\ p^C_{21} & 0 & \cdots & p^C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ p^C_{N1} & \cdots & \cdots & 0 \end{bmatrix} \circ \mathbf{A} = \begin{bmatrix} 1 & A_{\mathbf{x_1 x_2}} & \cdots & A_{\mathbf{x_1 x_M}} \\ A_{\mathbf{x_2 x_1}} & 1 & \cdots & A_{\mathbf{x_2 x_M}} \\ \vdots & \vdots & \ddots & \vdots \\ A_{\mathbf{x_M x_1}} & \cdots & \cdots & 1 \end{bmatrix}$$

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$$\mathbf{P} = \begin{bmatrix} p_{\mathbf{x_1x_1}} & p_{\mathbf{x_1x_2}} & \cdots & p_{\mathbf{x_1x_M}} \\ p_{\mathbf{x_2x_1}} & p_{\mathbf{x_2x_2}} & \cdots & p_{\mathbf{x_2x_M}} \\ \vdots & \vdots & \ddots & \vdots \\ p_{\mathbf{x_Mx_1}} & \cdots & \cdots & p_{\mathbf{x_Mx_M}} \end{bmatrix}$$

$$\boxed{\mathbf{P} = \{p_{\mathbf{xy}}\} = p_{ij}^{c} \cdot A_{\mathbf{xy}}}$$

Transient Markov Chain Analysis

$$\mathbf{P} = \begin{array}{c} \begin{array}{ccc} \text{TR} & \mathcal{LM} & \mathbf{x}^\star \end{array} \\ \left(\begin{array}{c:c:c} \underline{\mathbf{Q}} & \mathbf{R}_1 & \mathbf{R}_2 \\ \hdashline \mathbf{0} & \mathbf{I} & \mathbf{0} \\ \hdashline \mathbf{0} & \mathbf{0} & 1 \end{array}\right) \end{array} \begin{array}{c} \\ \text{TR} \\ \mathcal{LM} \\ \mathbf{x}^\star \end{array}$$

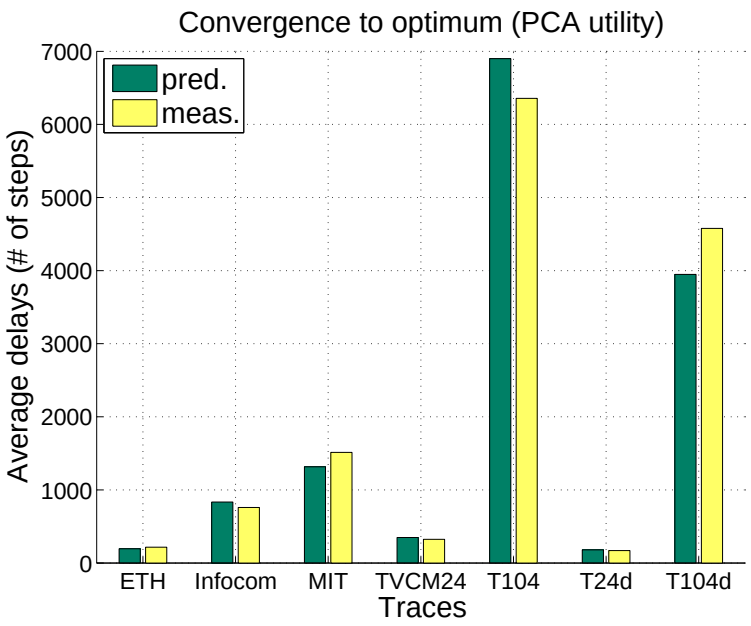
Fundamental matrix: $\mathbf{N} = (\mathbf{I} - \underline{\mathbf{Q}})^{-1}$

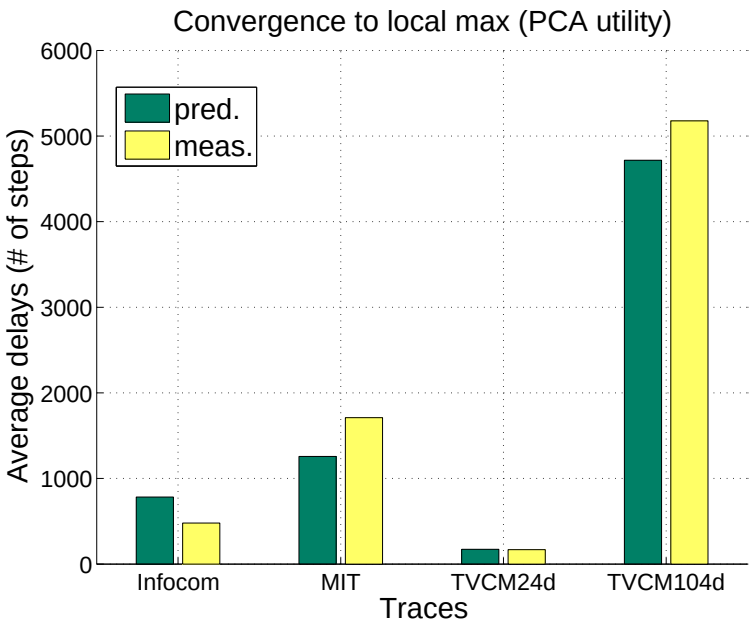
Convergence Probability

	Optimum		Local max.	
	pred.	meas.	pred.	meas.
ETH	1.0000	1.0000	N/A	N/A
Infocom	0.5267	0.5435	0.41321	0.39365
MIT	0.67726	0.55616	0.29571	0.14654
TVCM24	0.6086	0.5979	0.3913	0.4020
TVCM104	0.x	0.x	0.x	0.x

Table: Absorption probabilities

Average Convergence Delays





Conclusion

- New unified model for DTNs
  - Heterogeneous node mobility
  - Greedy algorithms
  - Randomized gradient-ascent algorithms
- Model usage
  - Mobility conditions for algorithm correctness
  - Convergence probability
  - Convergence delay

Outlook

- Model generality
  - routing
  - resource allocation (buffer management)
  - etc.
- Practical issues: state space size
  - State lumping
  - Approximations
  - Petri-nets

The End

Thank you for your attention.

Please, ask questions.