Heterogeneity in Contact Dynamics: Helpful or Harmful to Forwarding Algorithms in DTNs?

7th Intl. Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt'09)

June 24, 2009

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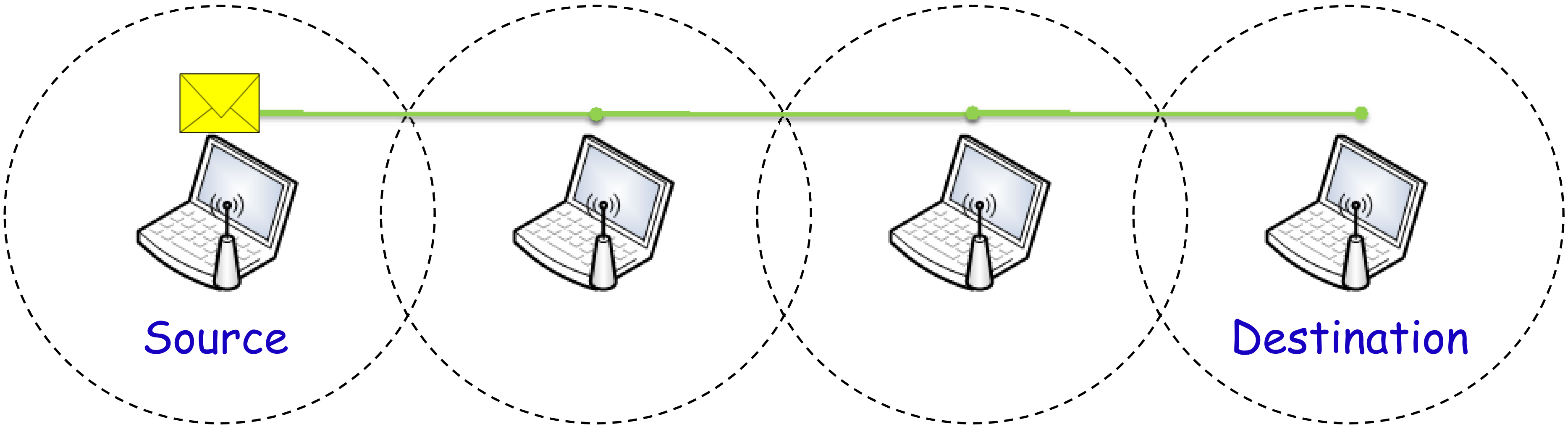
(Traditional) Mobile Ad-Hoc Networks (MANETs)

- End-to-end paths (connectivity) maintained
- Principle of Forwarding/Routing: Store-and-Forward



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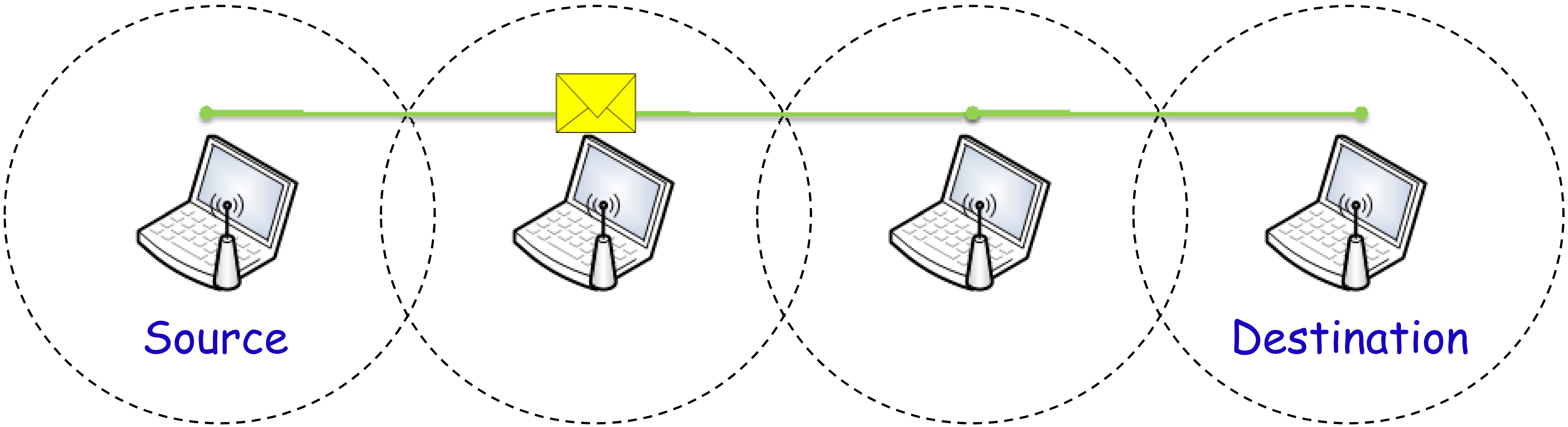

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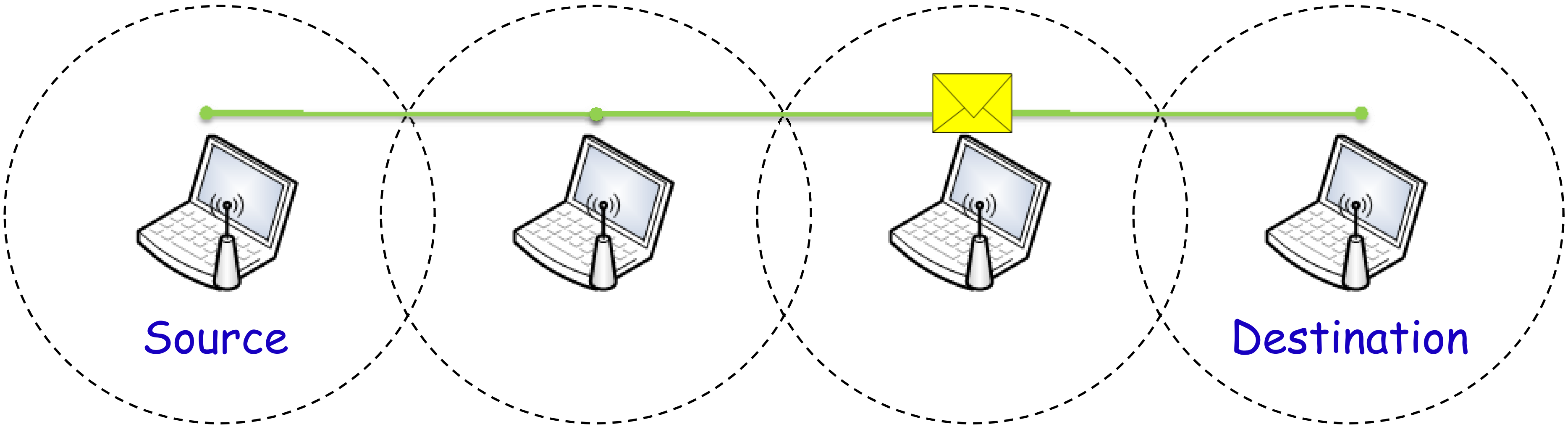

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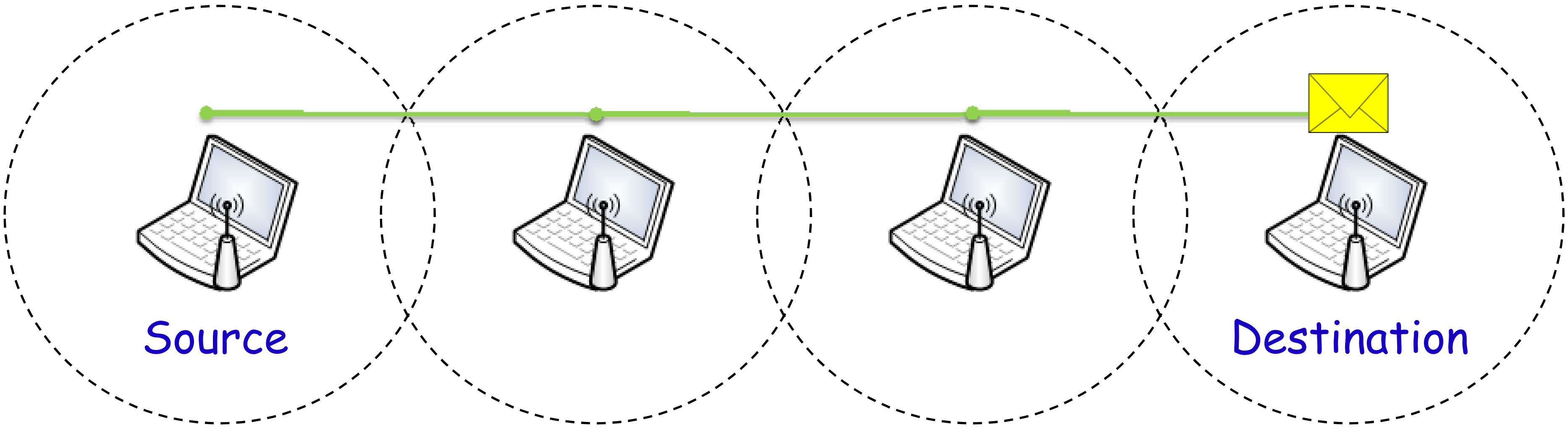

Disruption/Delay Tolerant Networks (DTNs)

- Node Mobility, Power limitations, etc → Intermittent Connectivity
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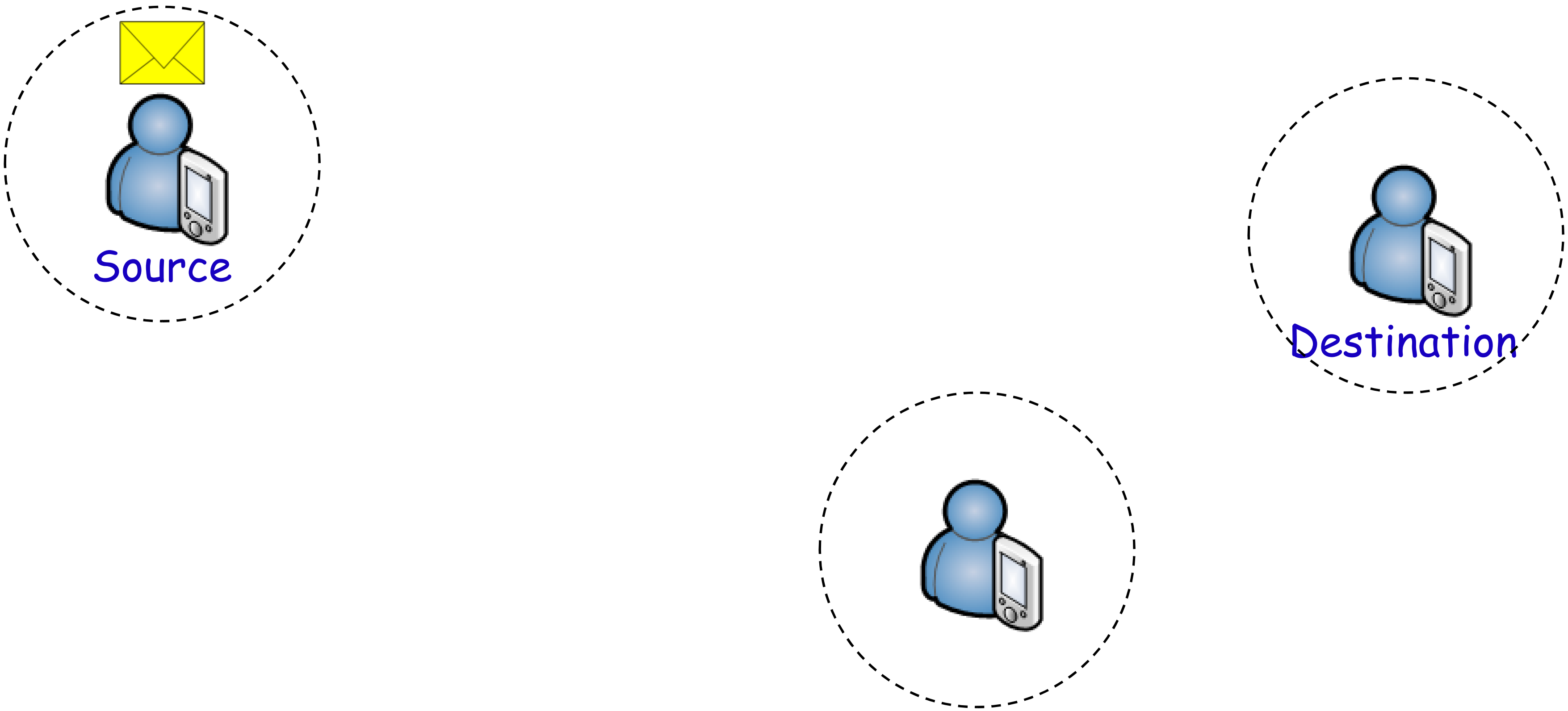

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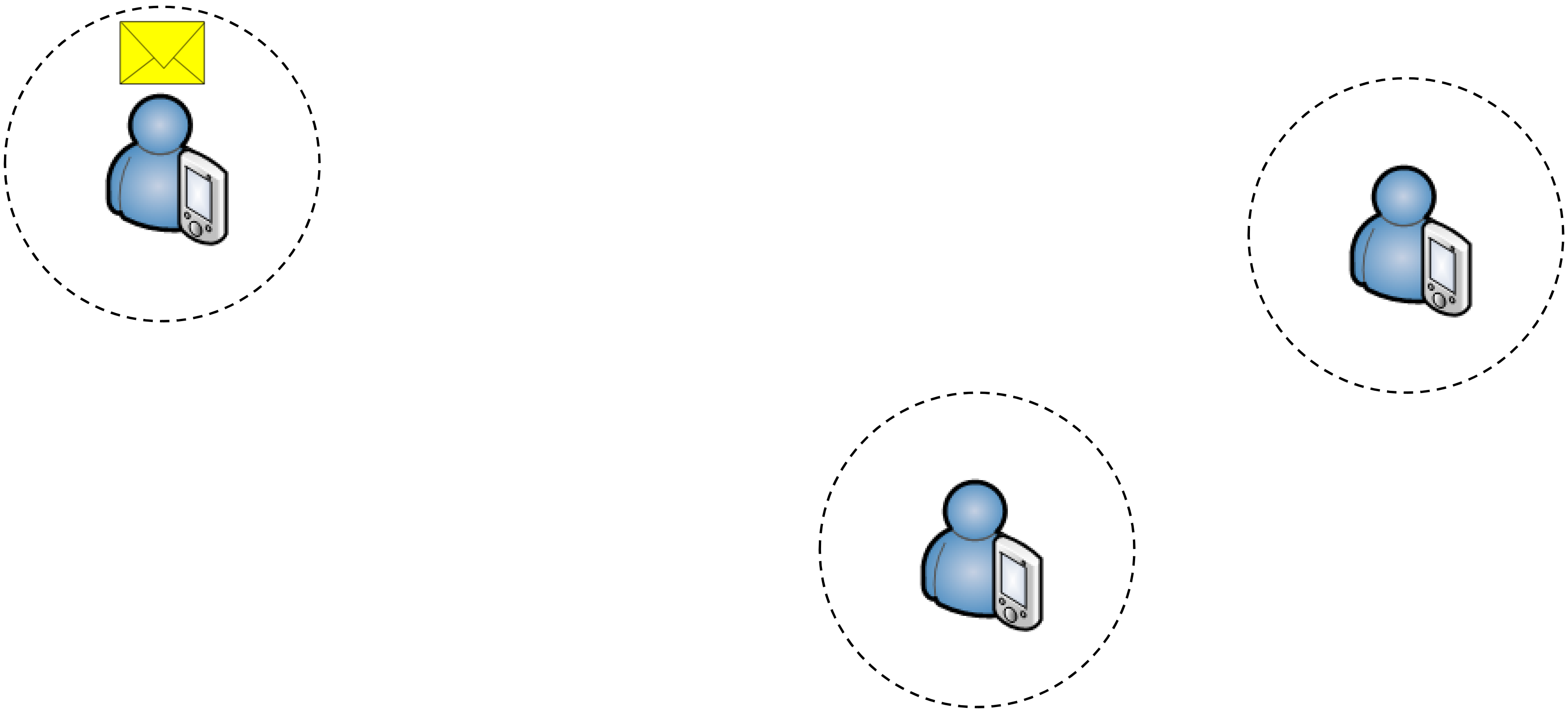

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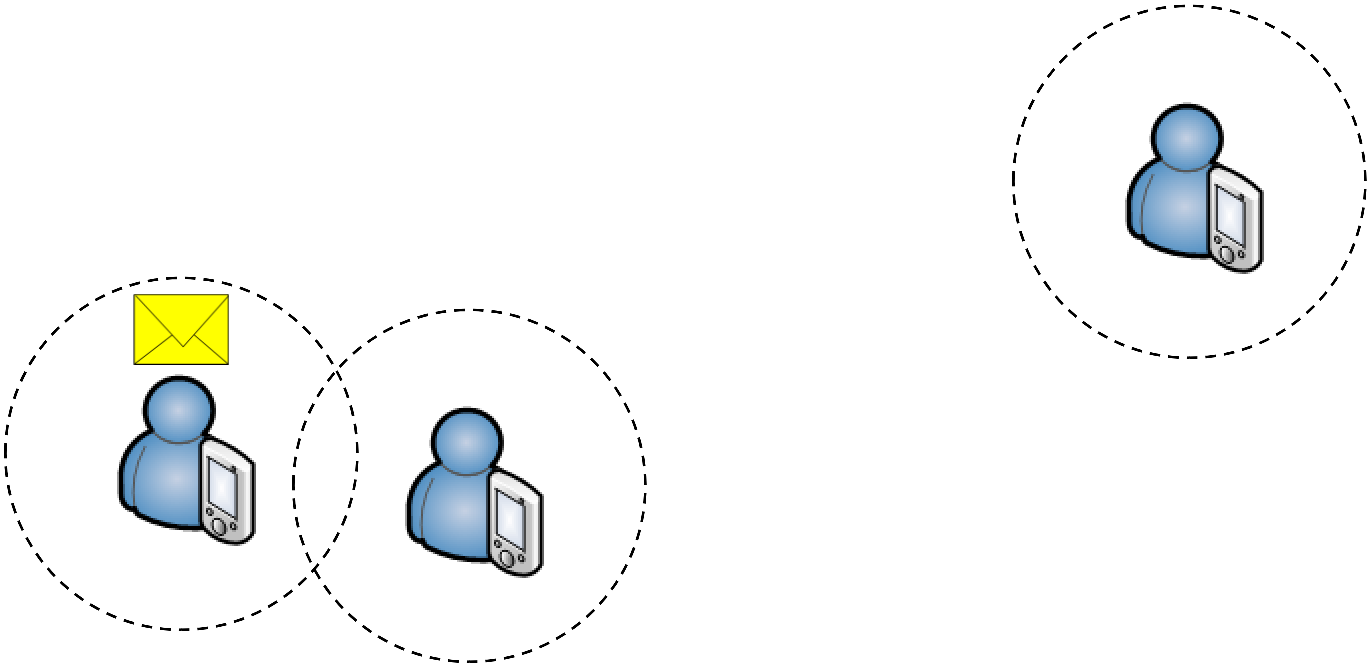

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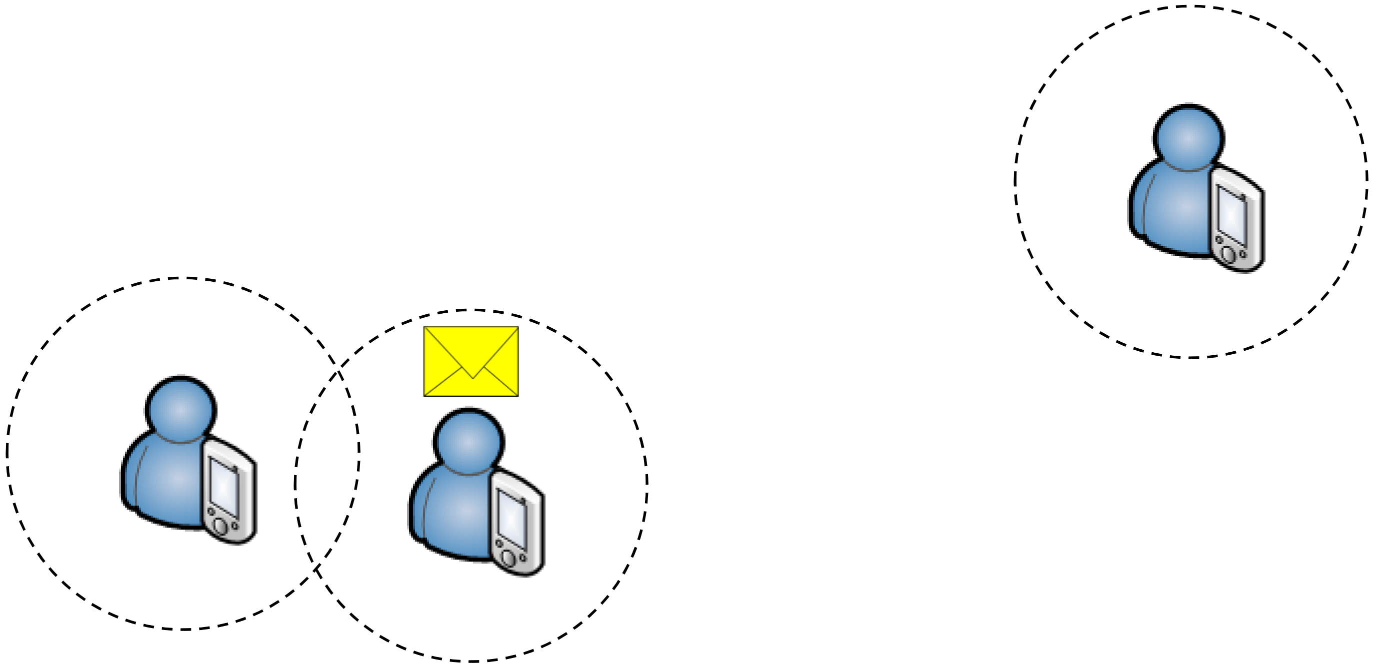

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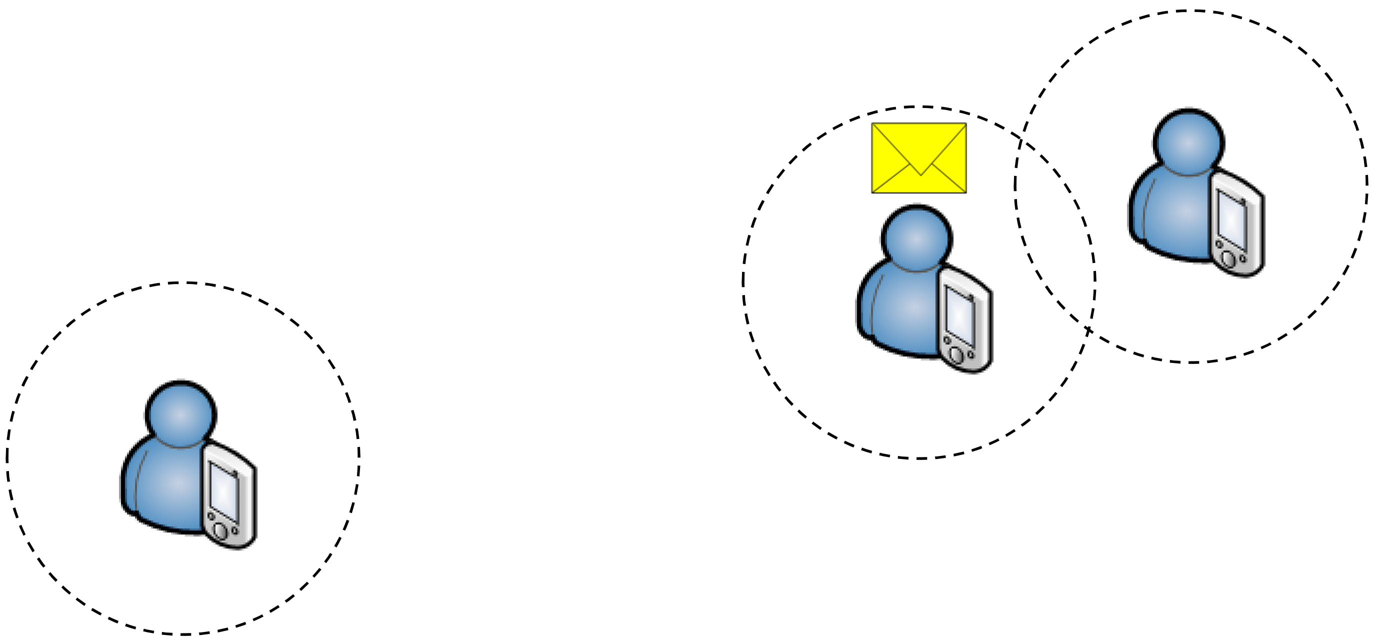

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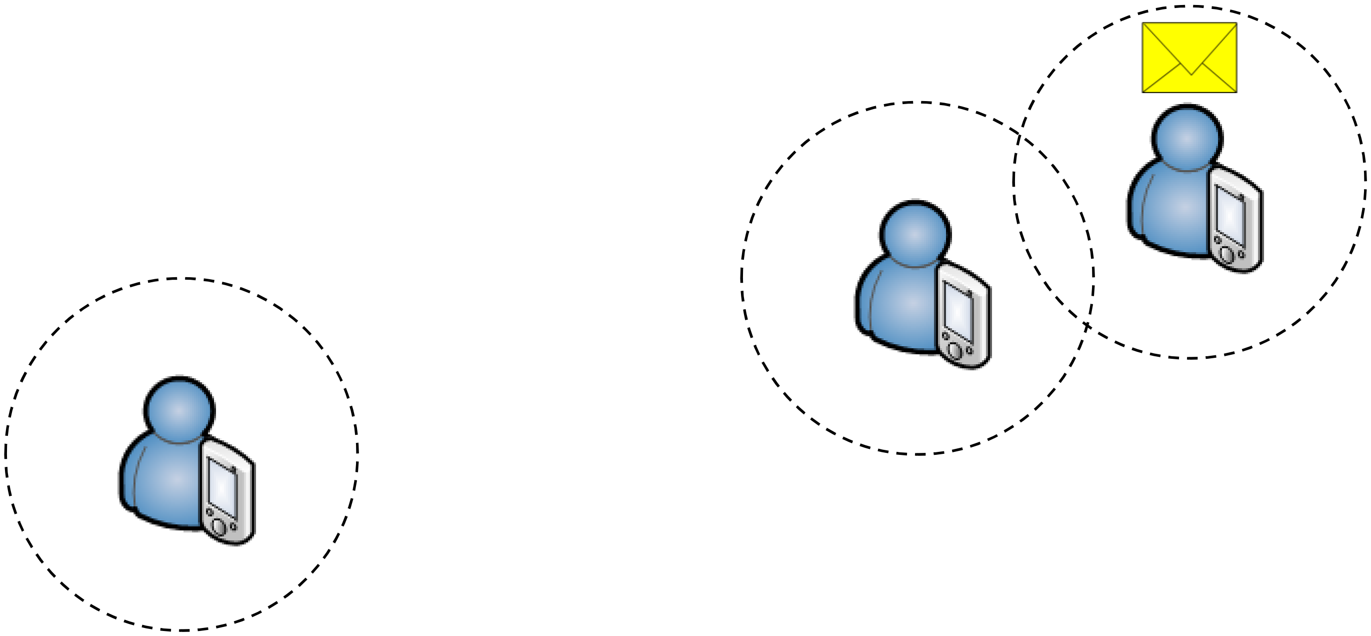


Disruption/Delay Tolerant Networks (DTNs)

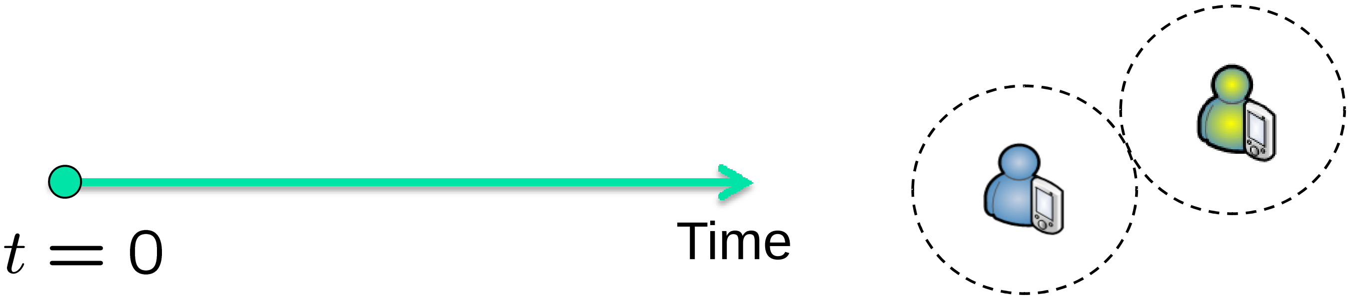
- Node Mobility, Power limitations, etc → Intermittent Connectivity
- Principle of Forwarding/Routing: Store-***Carry***-and-Forward

An end-to-end path (in the normal definition) doesn't exist!

However, message can be delivered eventually over *time* !!

Inter-contact Time

- In usual forwarding algorithms in DTNs, message transfer between two mobile nodes is done upon encounter



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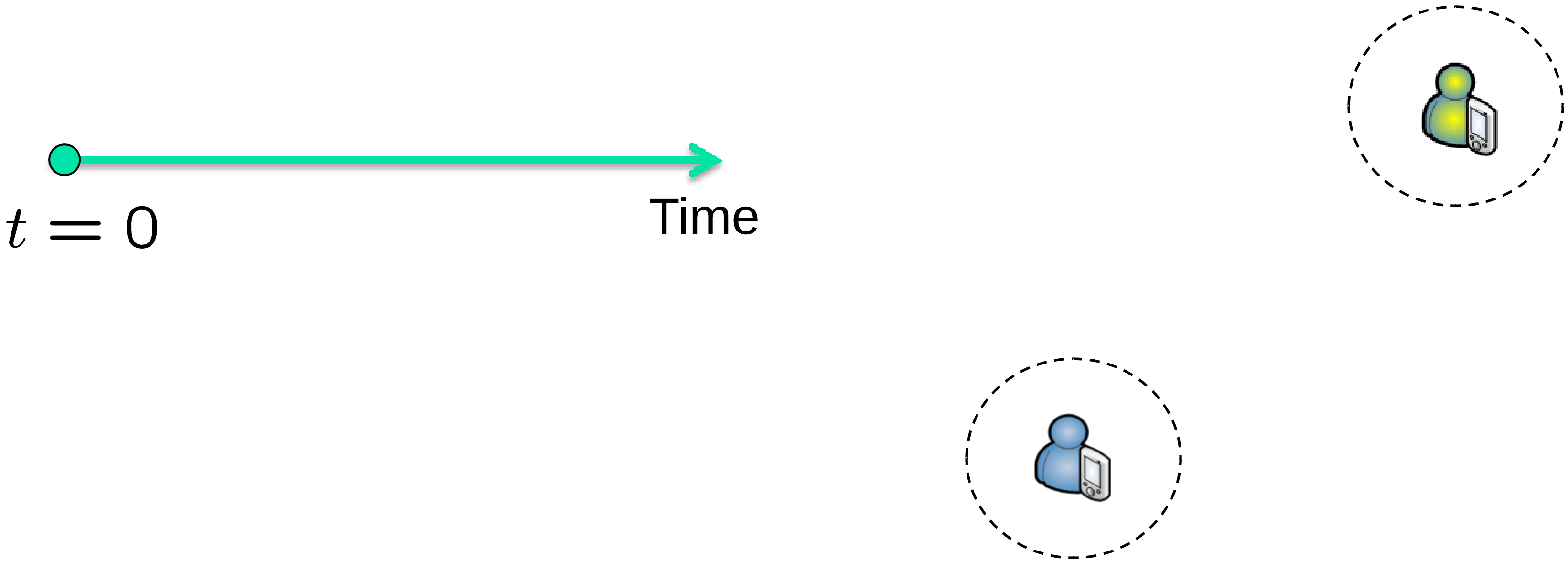

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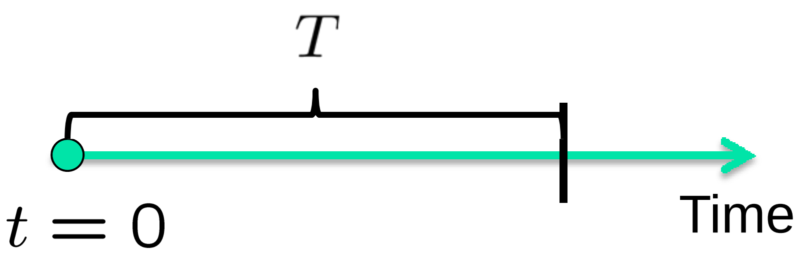
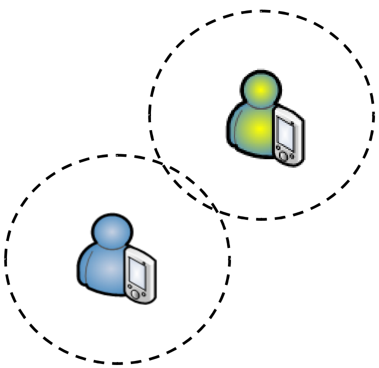




- **Inter-contact time:** how long two mobile nodes take to meet with each other again
- Need to know the characteristic of inter-contact time of a node pair

Inter-contact Time

- Pairwise inter-contact time distribution
  - Inter-contact time distribution of a given node pair $i \in \mathcal{I}$

    $\mathbb{P}\{T_i > t\}$

    ↑ Index set for node pairs

- Aggregate inter-contact time distribution
  - Inter-contact time distribution of a random node pair

    $$\mathbb{P}\{T_I > t\} = \mathbb{E}\{\mathbb{P}\{T_I > t|I\}\} = \sum_{i \in \mathcal{I}} \mathbb{P}\{T_i > t\}\frac{1}{|\mathcal{I}|}.$$

    I: random variable to indicate a random node pair, which is uniformly distributed over $\mathcal{I}$

  - The aggregated inter-contact time samples have been mainly used to uncover the characteristic of mobile nodes' contact pattern and to justify their modeling choices.

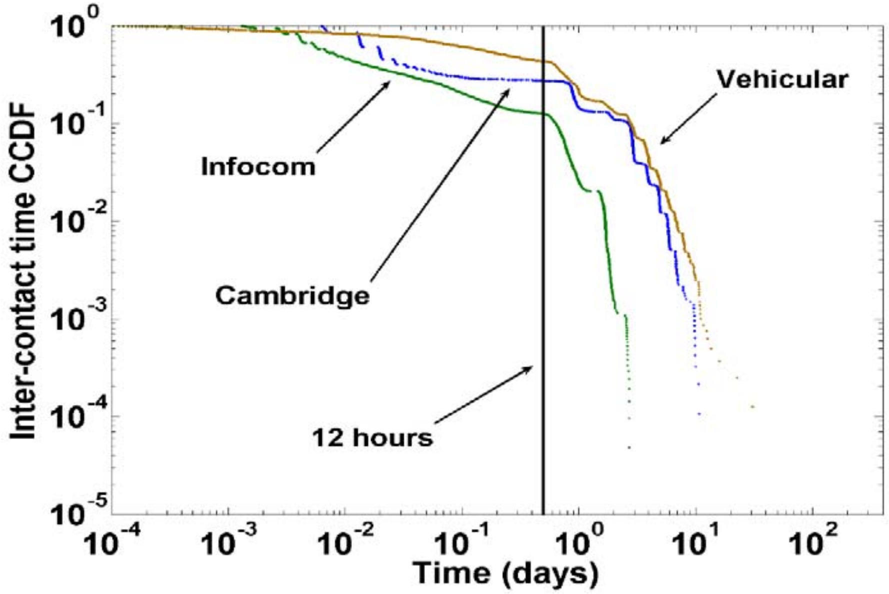
Motivation: What is in literature?

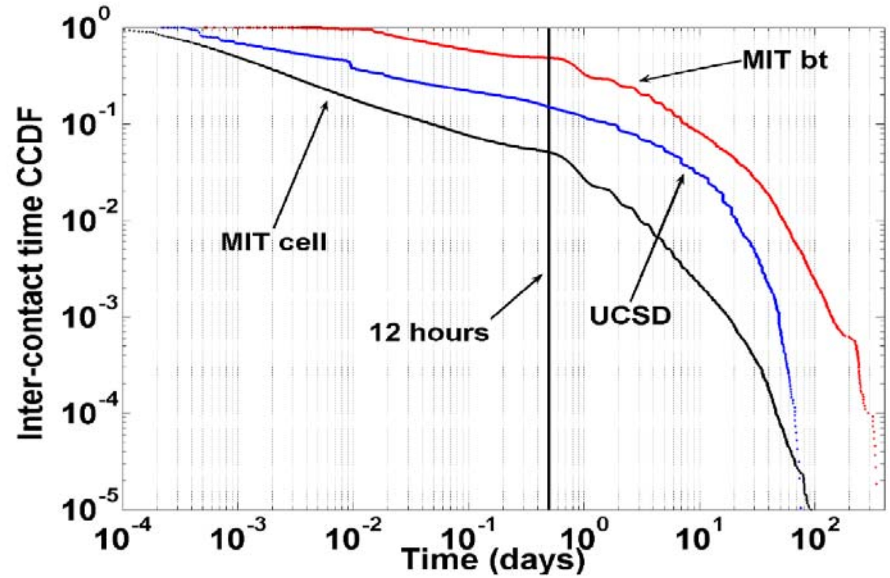
- Many analytical studies [1-6] have used "homogeneous model"
  - Contacts of any node pair occur according to a Poisson process. → Inter-contact time distribution of any node pair: exponential with same mean

- [1] T. Small and Z. Hass, "The shared wireless infostation model: a new ad hoc networking paradigm (or where there is a whale, there is a way)," in *Proc. of ACM MobiHoc '03*.
- [2] R. Groenevelt, G. Koole, and P. Nain, "Message delay in mobile ad hoc networks," in *Proc. Of Performance '05*.
- [3] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and wait: an efficient routing scheme for intermittently connected mobile networks," in *Proc. of WDTN '05*.
- [4] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, "Performance modeling of epidemic routing," *Computer Networks*, 2007.
- [5] O. Helgason and G. Karlsson, "On the effect of cooperation in wireless content distribution," in *Proc. of IEEE/IFIP WONS '08*.
- [6] E. Altman, T. Basar, and F. D. Pellegrini, "Optimal monotone forwarding policies in delay tolerant mobile ad-hoc networks," in *Proc. Of InterPerf '08*.

Motivation: What is in literature?

- Empirical inter-contact time distribution measured in real mobility traces does NOT follow a pure exponential !!





[Source: Karagiannis-MobiCom'07]

- T. Karagiannis, J. Le Boudec, and M. Vojnovic, "Power law and exponential decay of inter contact times between mobile devices." in *Proc. of ACM MobiCom '07*.
- H. Cai and D. Y. Eun, "Crossing over the bounded domain: from exponential to power-law inter-meeting time in MANET," in *Proc. of ACM MobiCom '07*.

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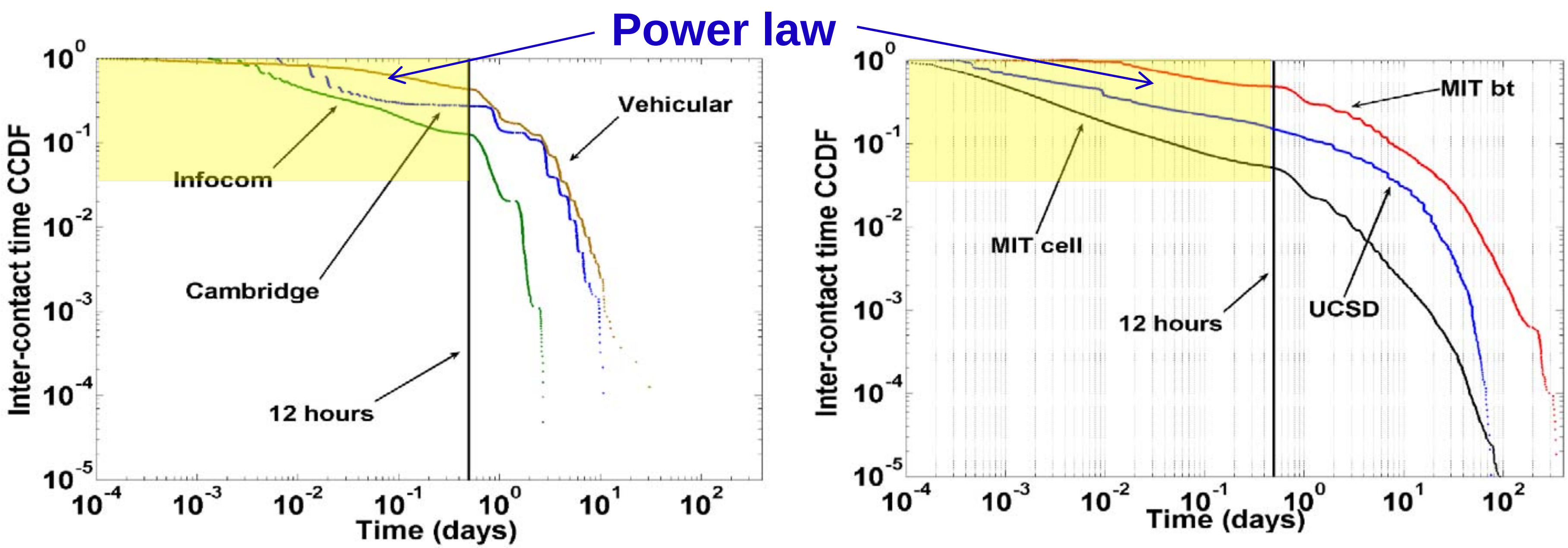

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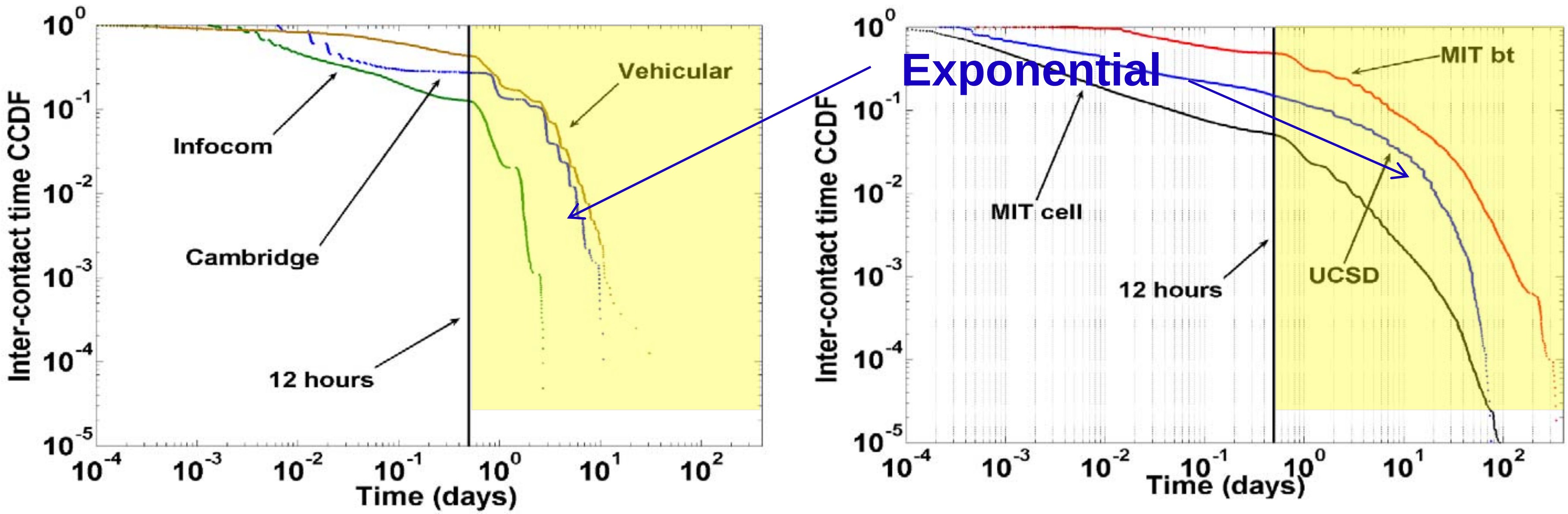

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Motivation: What is missing?

- Heterogeneity arises everywhere!
  - Make contact dynamics deviate from Poisson
- Many empirical studies [1-6] have shown the existence of heterogeneity structures and their characteristics.

- [1] W. Hsu, K. Merchant, C. Hsu, and A. Helmy, "Weighted waypoint mobility model and its impact on ad hoc networks," *ACM MC2R*, January 2005
- [2] N. Sarafijanovic-Djukic, M. Piorkowski, and M. Grossglauser, "Island hopping: efficient mobility-assisted forwarding in partitioned networks," in *Proc. of IEEE SECON '06*.
- [3] M. Musolesi and C. Mascolo, "A community based mobility model for ad hoc network research," in *Proc. of REALMAN '06*.
- [4] M. Boc, A. Fladenmuller, and M. D. de Amorim, "Towards self-characterization of user mobility patterns," in Proc. of *16th IST Mobile Summit '07*.
- [5] V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proc. Of Autonomics '07*.
- [6] P. Hui, J. Crowcroft, and E. Yoneki, "BUBBLE Rap: Social-based Forwarding in Delay Tolerant Networks," in *Proc. of ACM MobiHoc '08*.

Motivation: What is missing?

NCSU campus map

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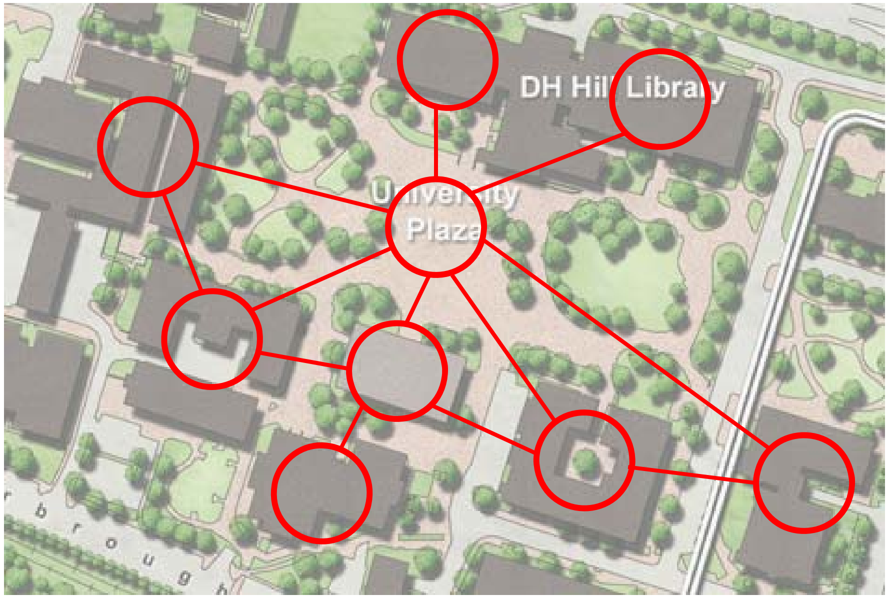

- Several popular places (e.g., library, dormitory, or dining hall) in a campus
  → Spatially heterogeneous structure

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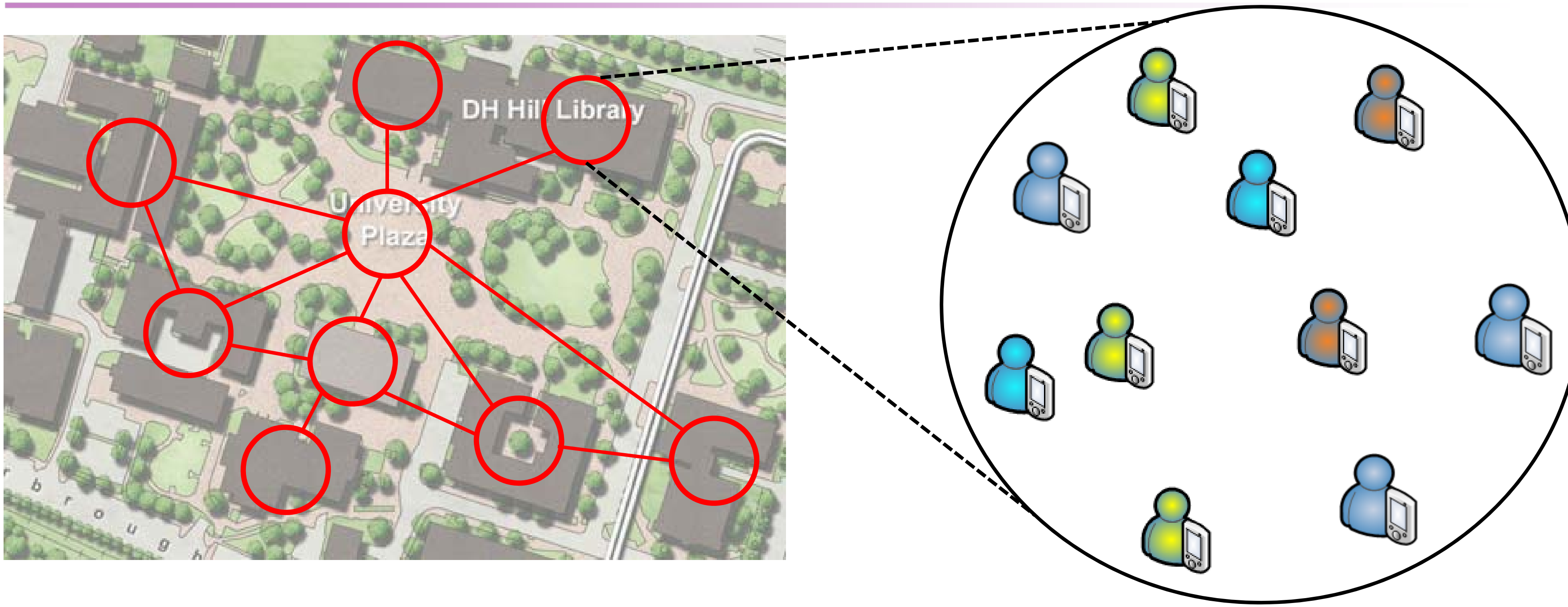

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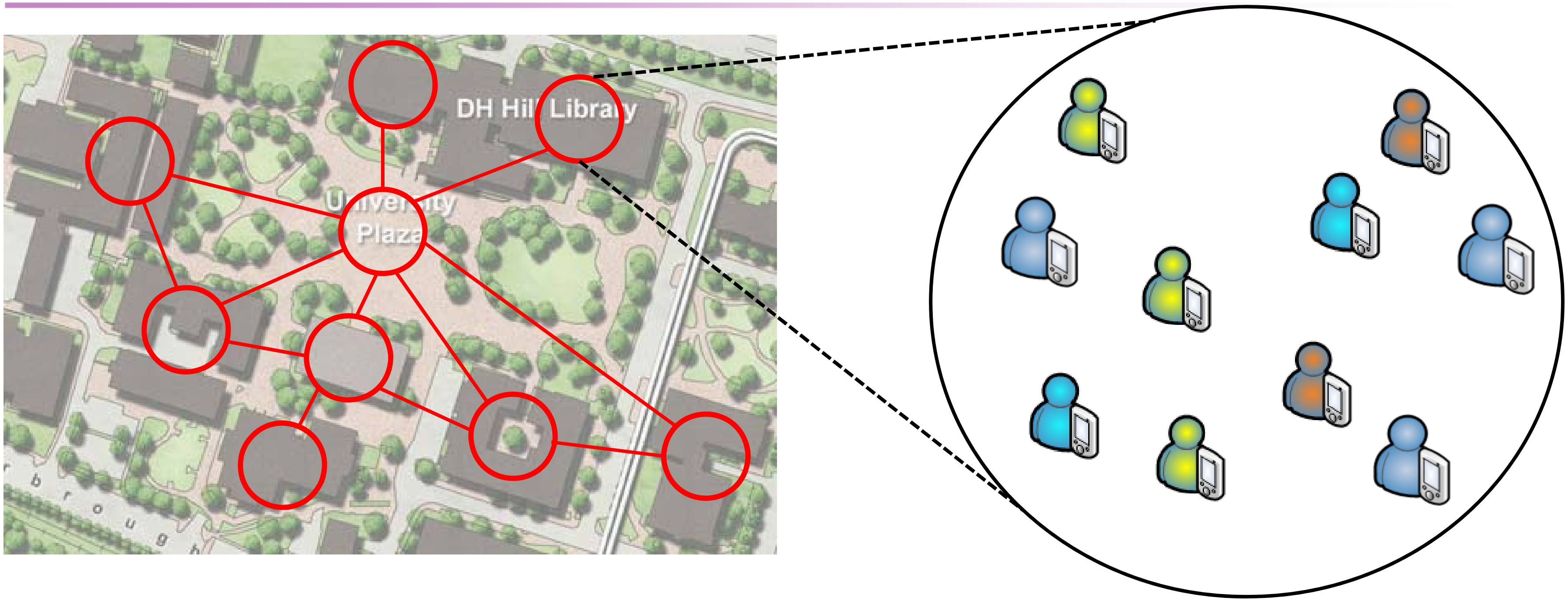


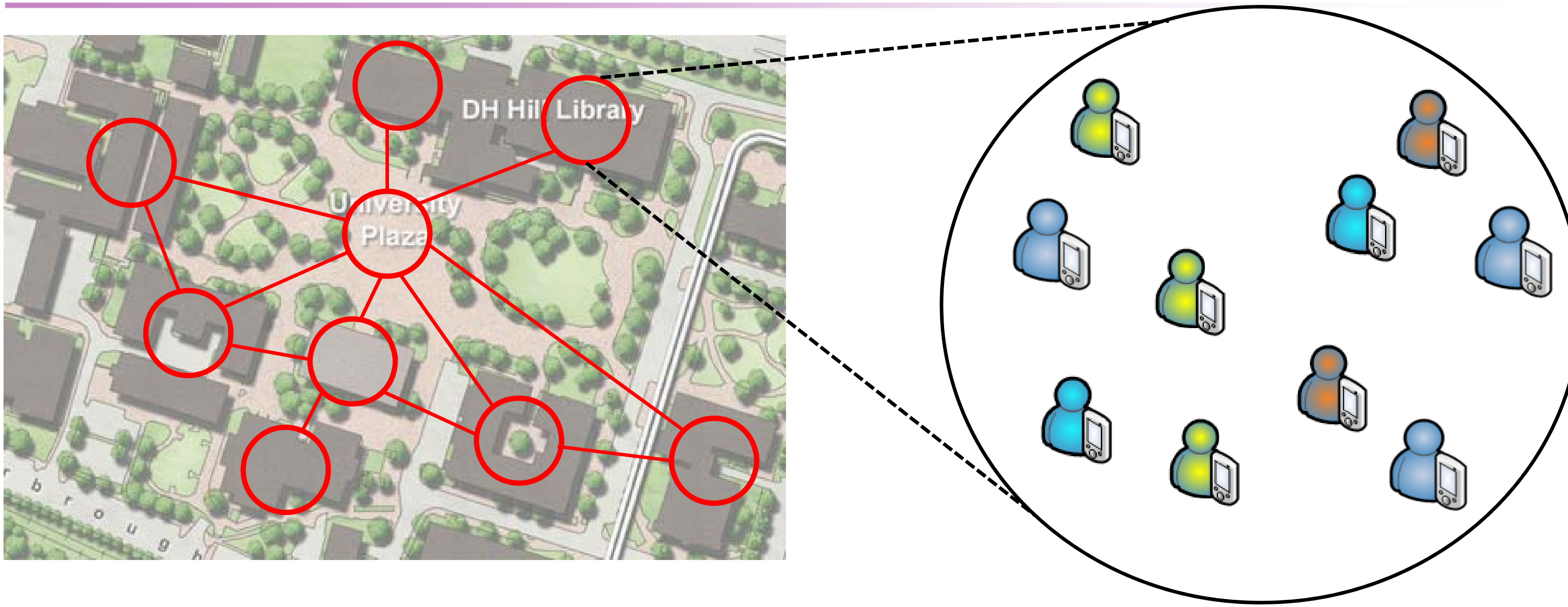
- Several popular places (e.g., library, dormitory, or dining hall) in a campus

  → Spatially heterogeneous structure

- In each spatial cluster, students from different groups (e.g., ECE/CS departments or undergraduate/graduate) mix together

  → Individually (or socially) heterogeneous structure

Motivation: What is missing?



Two main sources of heterogeneity affect mobile nodes' contact dynamics!

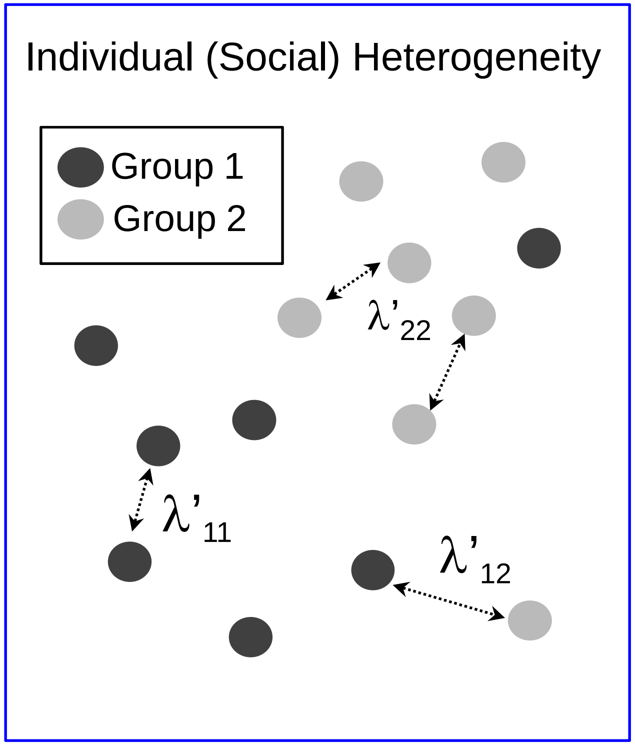
From Motivation to Our Work

- Use two representative heterogeneous network models – mathematically tractable
  1. Individually heterogeneous network model [1-2]
  2. Spatially heterogeneous network model [3]

- How heterogeneity in mobile nodes' contact dynamics impact the performance of routing/forwarding algorithms in DTNs, along with capturing the non-Poisson contact dynamics?

- [1] V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proc. Of Autonomics '07*.
- [2] V. Conan, J. Leguay, and T. Friedman, "Fixed Point Opportunistic Routing in Delay Tolerant Networks," *IEEE JSAC*, June 2008.
- [3] N. Banerjee, M. D. Corner, D. Towsley, and B. N. Levine, "Relays, base stations, and meshes: enhancing mobile networks with infrastructure," in *Proc. of MobiCom '08*.

Individually heterogeneous network model (Individual model)



Model Description --

- The inter-contact time distribution between two nodes (i,j) is exponential with λ_{ij}
- Heterogeneity: different contact rate λ_{ij} for nodes (i,j)

- V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proc. Of Autonomics '07*.
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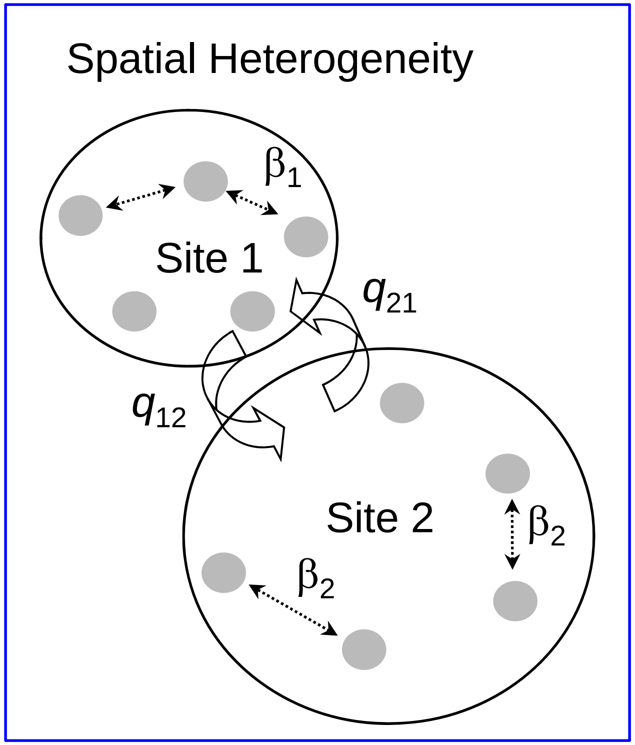
Spatially heterogeneous network model (spatial model)



Model Description --

- Move between spatial clusters
- Given that two mobile nodes *(i,j)* reside in same spatial cluster *k*, their inter-contact time distribution is exponential with β_k
- Heterogeneity: different contact rate β_k in each spatial cluster *k*
- Assume $q_{ij} = q_{ji}$ (equal transition rate between two spatial cluters)

- N. Banerjee, M. D. Corner, D. Towsley, and B. N. Levine, "Relays, base stations, and meshes: enhancing mobile networks with infrastructure," in *Proc. of MobiCom '08*.

Inter-contact time in heterogeneous models

- The aggregate inter-contact time distribution under individual model → a weighted sum of exponentials (hyper-exponential) [1]

$$\mathbb{P}\{T_I^{in} > t\} = \mathbb{E}\{e^{-t/X_{in}}\}$$

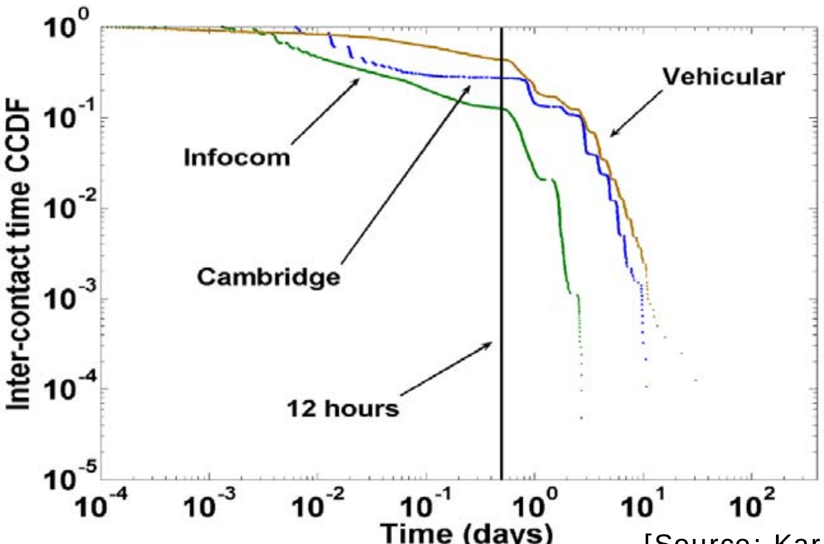
- **Proposition**: The pairwise inter-contact time distribution of a given node pair *i* under spatial model is a hyper-exponential distribution. → Same distribution for the aggregate inter-contact time

$$\mathbb{P}\{T_I^{sp} > t\} = \mathbb{E}\{e^{-t/X_{sp}}\}$$

- [1] V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proc. Of Autonomics '07*.

Inter-contact time in heterogeneous models

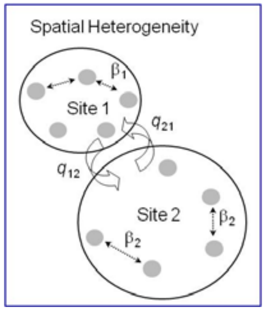
- Hyper-exponential distributions can be used to approximate a large class of distributions with *complete monotone* density [1,2]
- Both models yield hyper-exponential aggregated inter-contact time distribution → can capture non-exponential inter-contact time distribution empirically observed!!



[Source: Karagiannis-MobiCom'07]

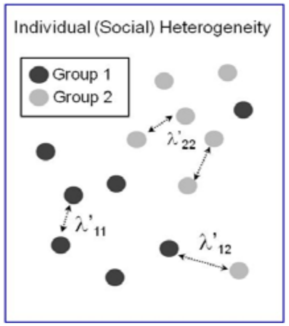
- [1] W. Feller, *An introduction to probability theory and its applications*. John Wiley & Son, 1968.
- [2] A. Feldmann and W. Whitt, "Fitting mixtures of exponentials to long-tail distributions to analyze network performance models," in *Proc. of IEEE INFOCOM '97*.

Our Work

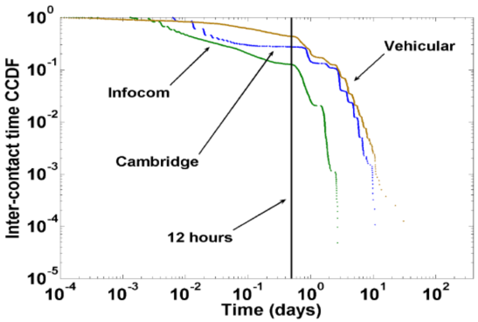


Spatial Model

Individual Model



Hyper-exponential Aggregate Inter-contact Time Distribution



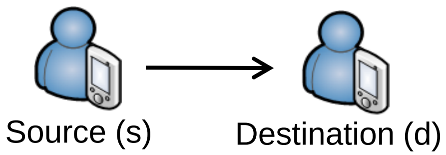
Impact of Heterogeneity on Forwarding Algorithms

Our Work – our analysis will answer

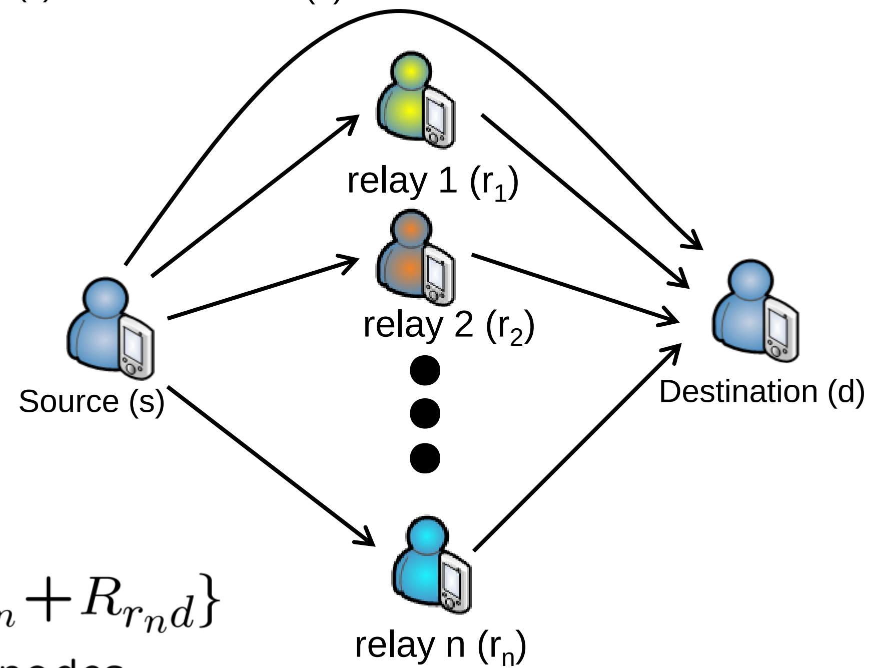
- Question I: How each heterogeneity structure in contact dynamics affects the forwarding performance as compared to that under homogeneous model?
  - Performance comparison (between hetero. model and homo. model) under the same average aggregated inter-contact time condition
- Question II: What happens if the aggregate inter-contact time distributions under both heterogeneous models are precisely matched?
  - Is the aggregate inter-contact time statistic (whole distribution) sufficient to predict the forwarding performance?

Test Case Forwarding Protocols

- Direct Forwarding (One-hop Forwarding)
  - Delay: Remaining (residual) inter-contact time of s-d pair



- Multicopy two-hop relay protocol [1,2]
  - Delay: Minimum delay over a direct path of s-d pair and all the relay paths



$$D \stackrel{d}{=} \min\{R_{sd}, R_{sr_1}+R_{r_1d}, \ldots, R_{sr_n}+R_{r_nd}\}$$

R_{ij}: residual inter-contact time of two nodes (i, j), where $i, j \in \{s, r_1, \ldots, r_n, d\}$

- [1] R. Groenevelt, G. Koole, and P. Nain, “Message delay in mobile ad hoc networks,” in *Proc. Of Performance ’05*.
- [2] A. Al-Hanbali, A. A. Kherani, and P. Nain, “Simple models for the performance evaluation of a class of two-hop relay protocols,” in *Proc. of IFIP Networking ’07*.

Results I

- Comparison Criterion - Same average aggregated inter-contact time over all node pairs

	Spatial vs. Homo.	Individual vs. Homo.
Direct Forwarding	$D_{sp} \geq_{st} D_{ho}$	$D_{in} \geq_{cx} D_{ho}$
Multicopy Two-hop Relay	$D_{sp} \geq_{st} D_{ho}$	$\mathbb{E}\{D_{in}\} \leq \mathbb{E}\{D_{ho}\}$

Results I – Average Delay

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$$\mathbb{E}\{D_{in}\} \leq \mathbb{E}\{D_{ho}\} \leq \mathbb{E}\{D_{sp}\}$$

- The underlying heterogeneity structure captured in each heterogeneous model yields a totally different delay performance.

Results I – Spatial vs. Homo.

- Comparison Criterion - Same average aggregated inter-contact time over all node pairs

	Spatial vs. Homo.
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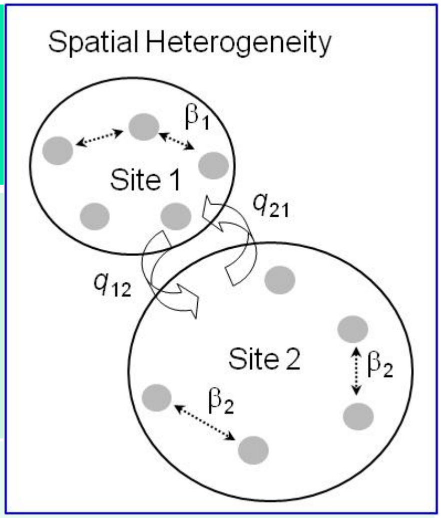
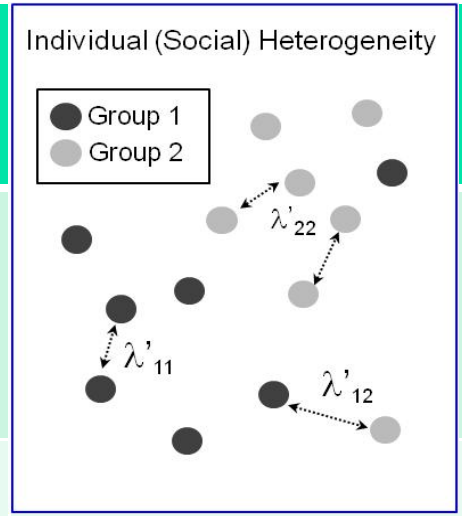


- Then, D_{sp} is *stochastically larger* than D_{ho}

$$\mathbb{P}\{D_{sp} > t\} \geq \mathbb{P}\{D_{ho} > t\} \text{ for all } t \geq 0 \Longrightarrow \mathbb{E}\{D_{sp}\} \geq \mathbb{E}\{D_{ho}\}$$

Results I – Individual vs. Homo.

- Comparison Criterion - <u>Same average aggregated inter-contact time</u> over all node pairs



	Individual vs. Homo.
Direct Forwarding	$D_{in} \geq_{cx} D_{ho}$
Multicopy Two-hop Relay	$\mathbb{E}\{D_{in}\} \leq \mathbb{E}\{D_{ho}\}$

Path Diversity

- D_{in} is *larger* than D_{ho} in the convex order

$\mathbb{E}\{\phi(D_{in})\} \geq \mathbb{E}\{\phi(D_{ho})\}$ for all convex functions ϕ

⟹ Var$\{D_{in}\} \geq$ Var$\{D_{ho}\}$

Results I – Summary

- Comparison Criterion - Same average aggregated inter-contact time over all node pairs

Heterogeneity in the **spatially** heterogeneous network model **deteriorates** the forwarding/routing performance when compared with that under homogeneous model

Heterogeneity in the **individually** heterogeneous network model **improves** the forwarding/routing performance when compared with that under homogeneous model

Results II

- Comparison Criterion - Entire aggregated inter-contact time distributions for the spatial and individual models are precisely matched

	Spatial vs. Individual
Direct Forwarding	$D_{sp} \geq_{st} D_{in}$

- Performance gap between both heterogeneous models & Aggregate inter-contact time distribution is insufficient to predict the performance of forwarding algorithms

Conclusion

- Showed each heterogeneous model correctly captures the non-Poisson contact dynamics observed in real traces.

- Proved that each heterogeneous model predicts an entirely opposite delay performance when compared with that under the homogeneous model
  - Heterogeneity in spatial model is harmful to the forwarding performance
  - Heterogeneity in individual model is helpful to the forwarding performance

- Merely capturing non-Poisson contact dynamics – even if the *entire distribution* of aggregated inter-contact time is precisely matched, is still not enough

Thank You!!