Exploiting Heterogeneity in Mobile Opportunistic Networks: An Analytic Approach

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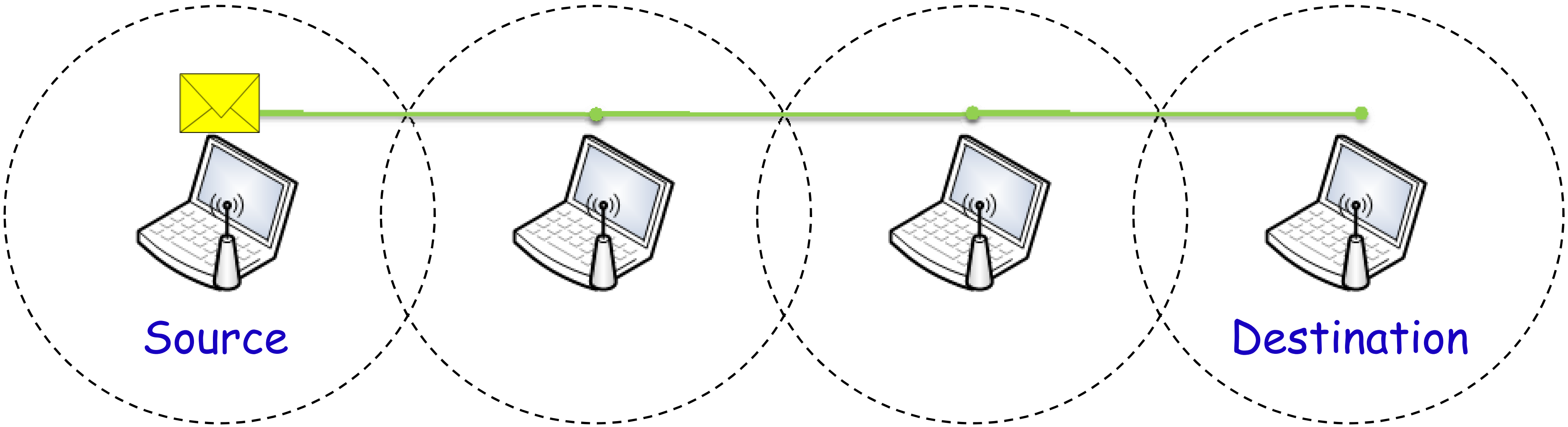
(Traditional) Mobile Ad-Hoc Networks (MANETs)

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



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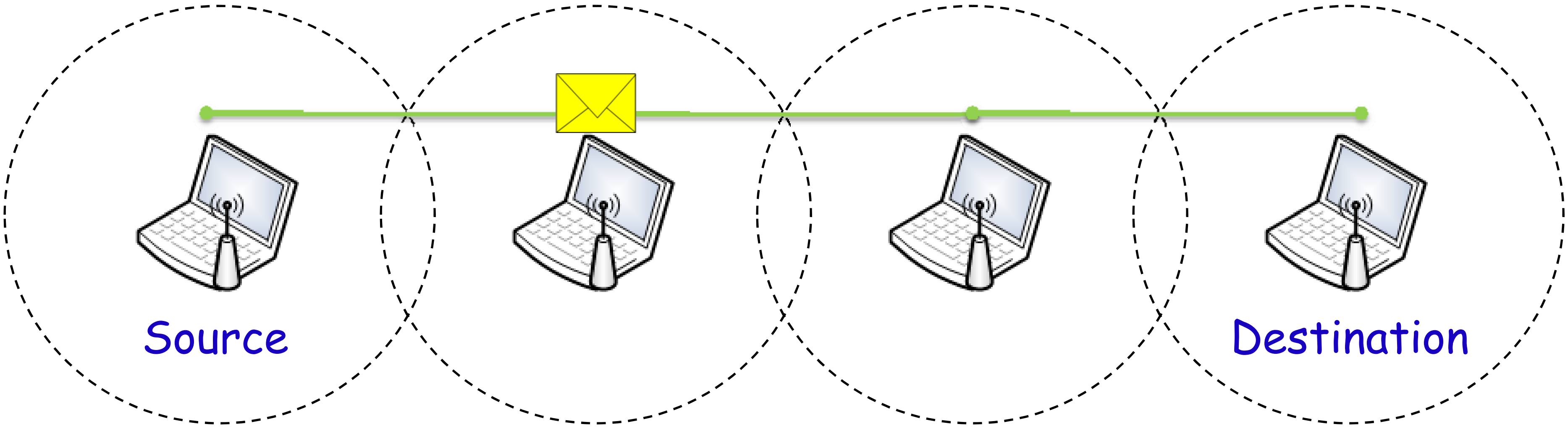

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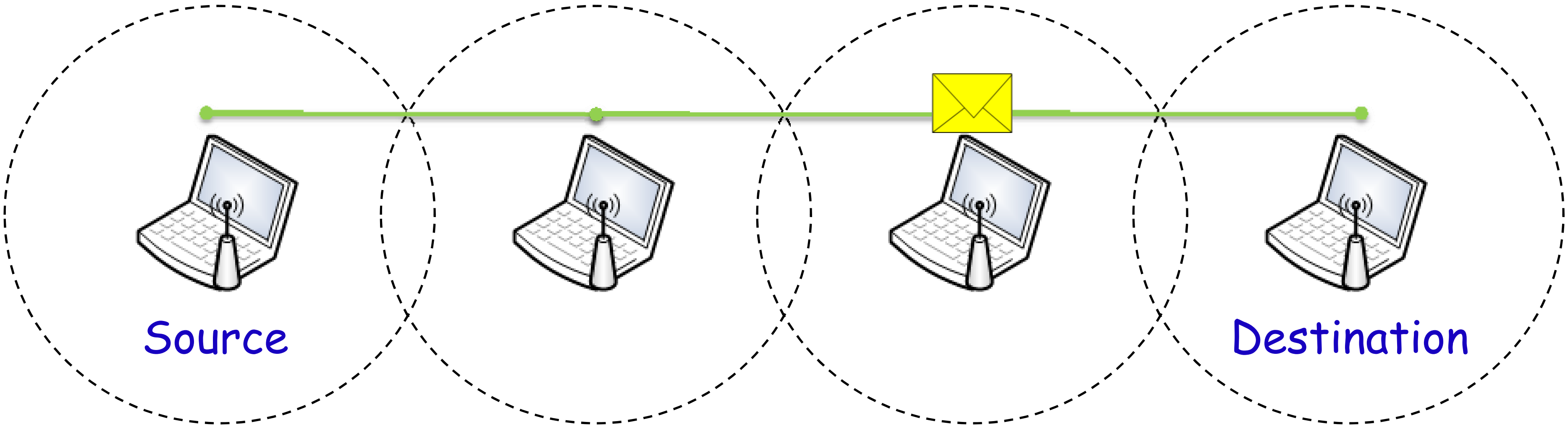

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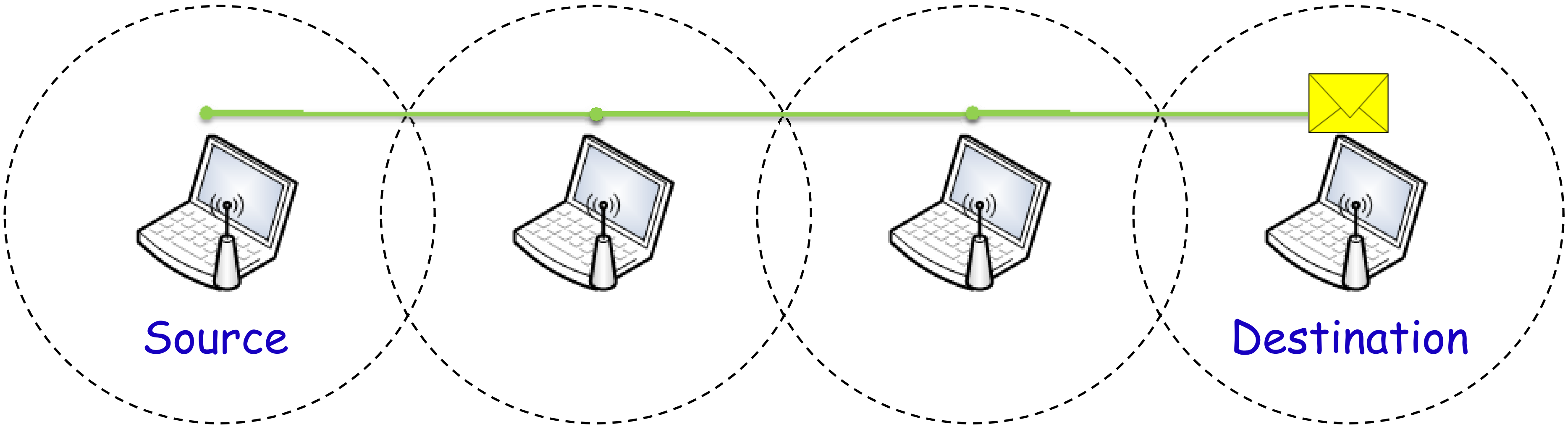
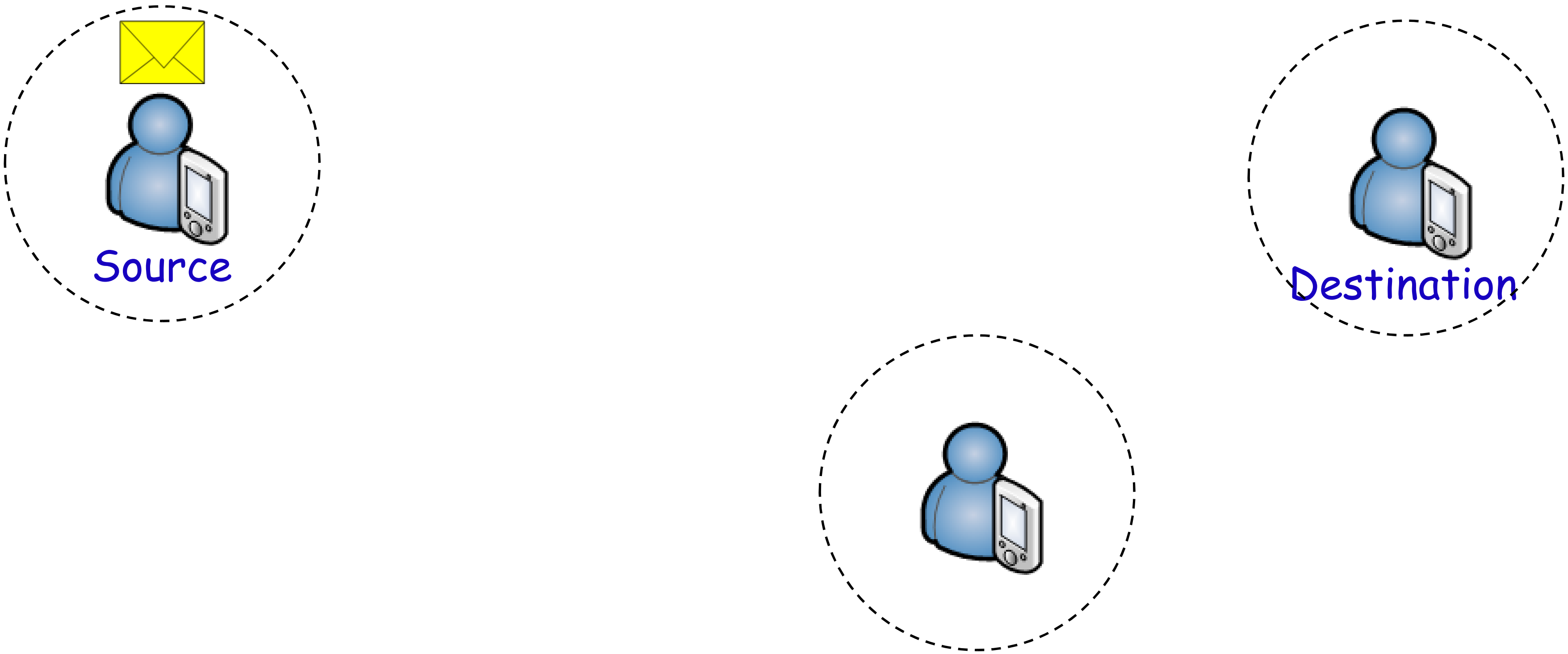


Mobile Opportunistic Networks (MONs)

- Disruption/Delay Tolerant Networks (DTNs)
- Node Mobility, Power limitations, etc → Intermittent Connectivity
- Principle of Forwarding/Routing: <u>Store-***Carry***-and-Forward</u>



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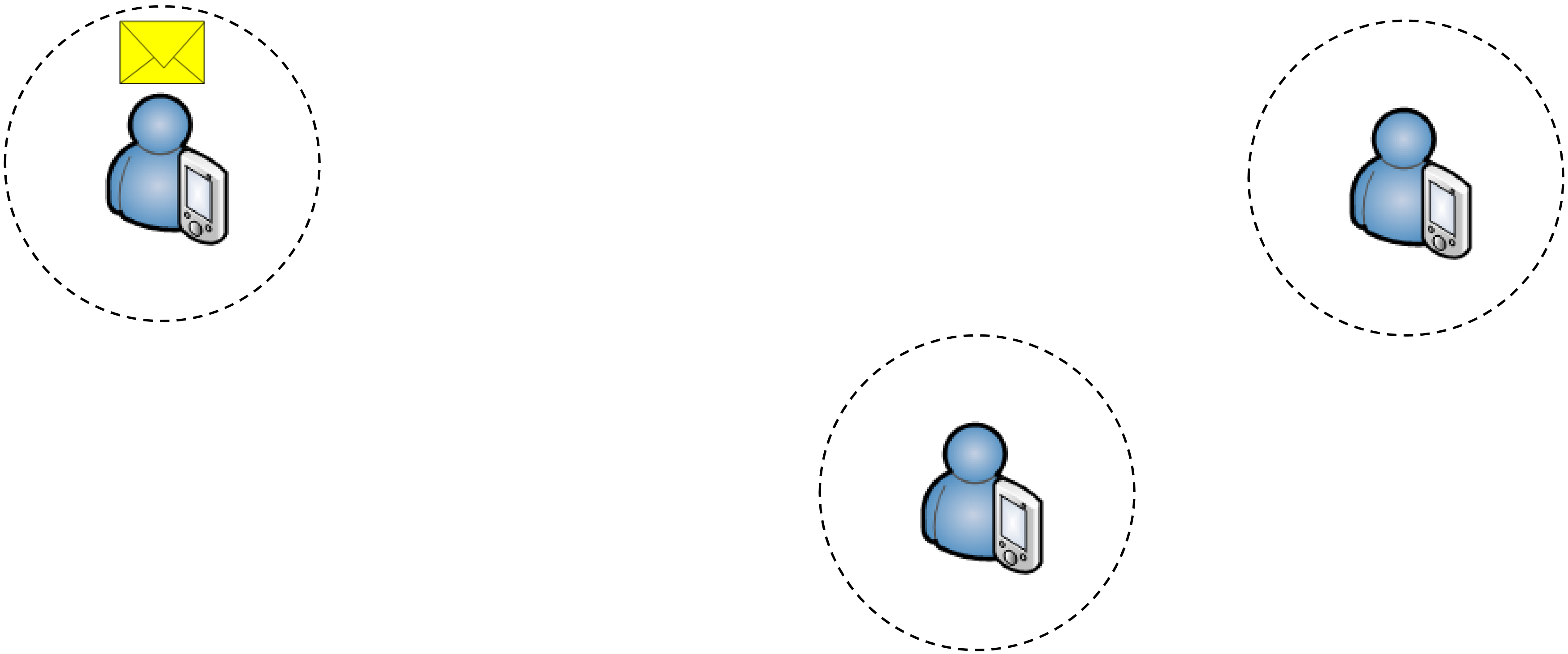

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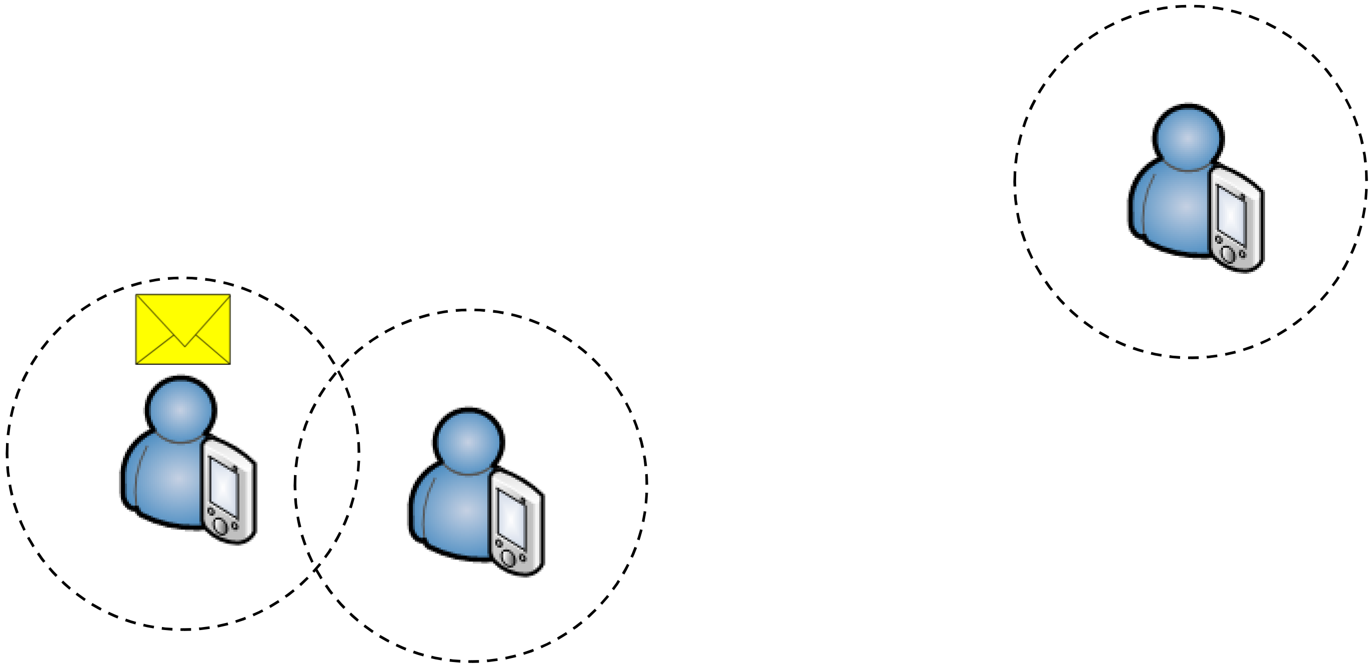

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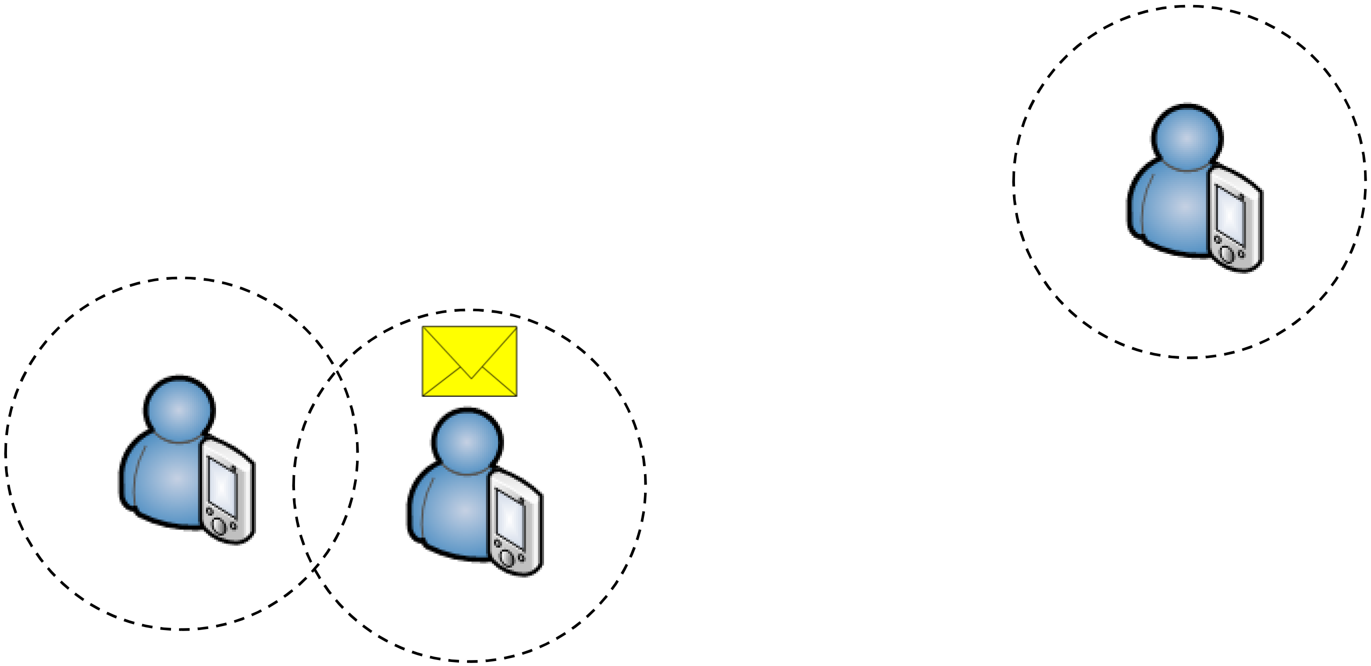

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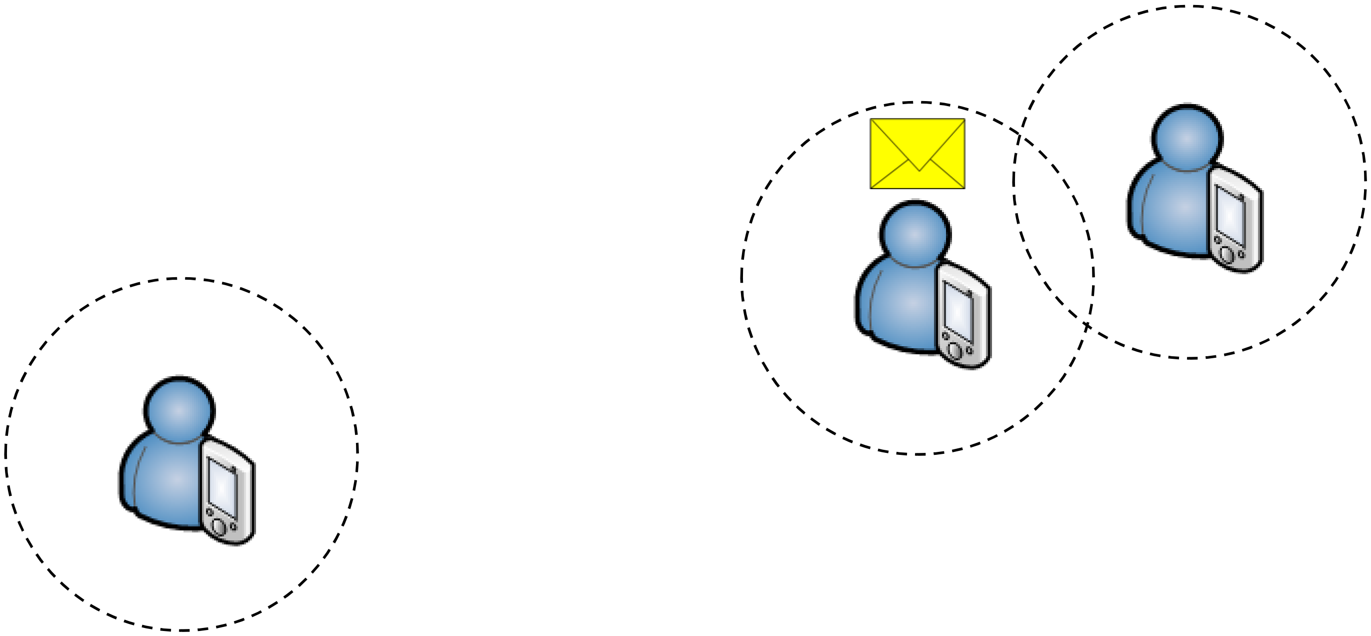

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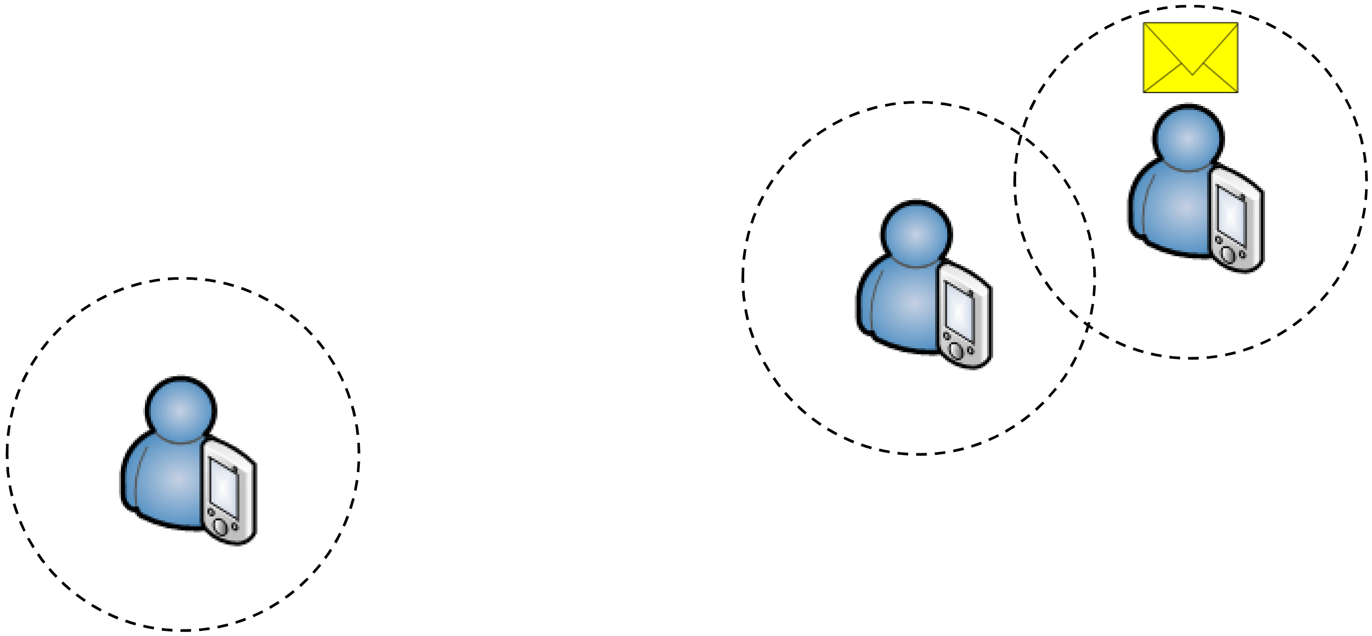

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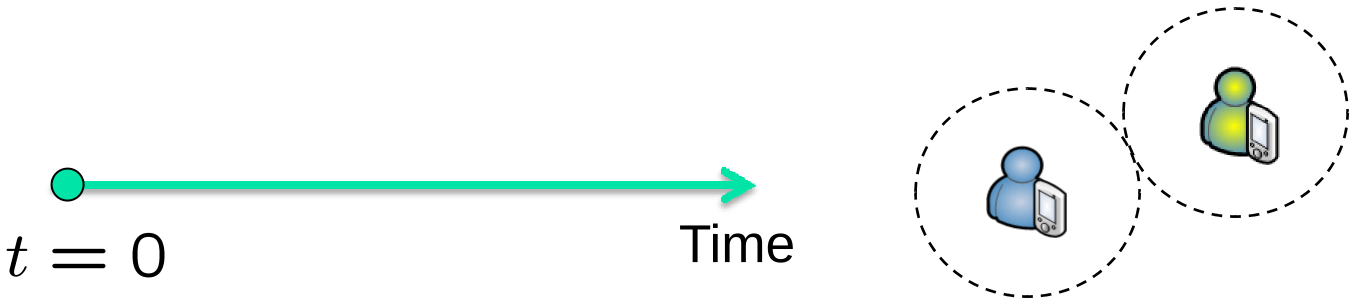
An end-to-end path (in the normal definition) doesn't exist!

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

Inter-contact Time

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



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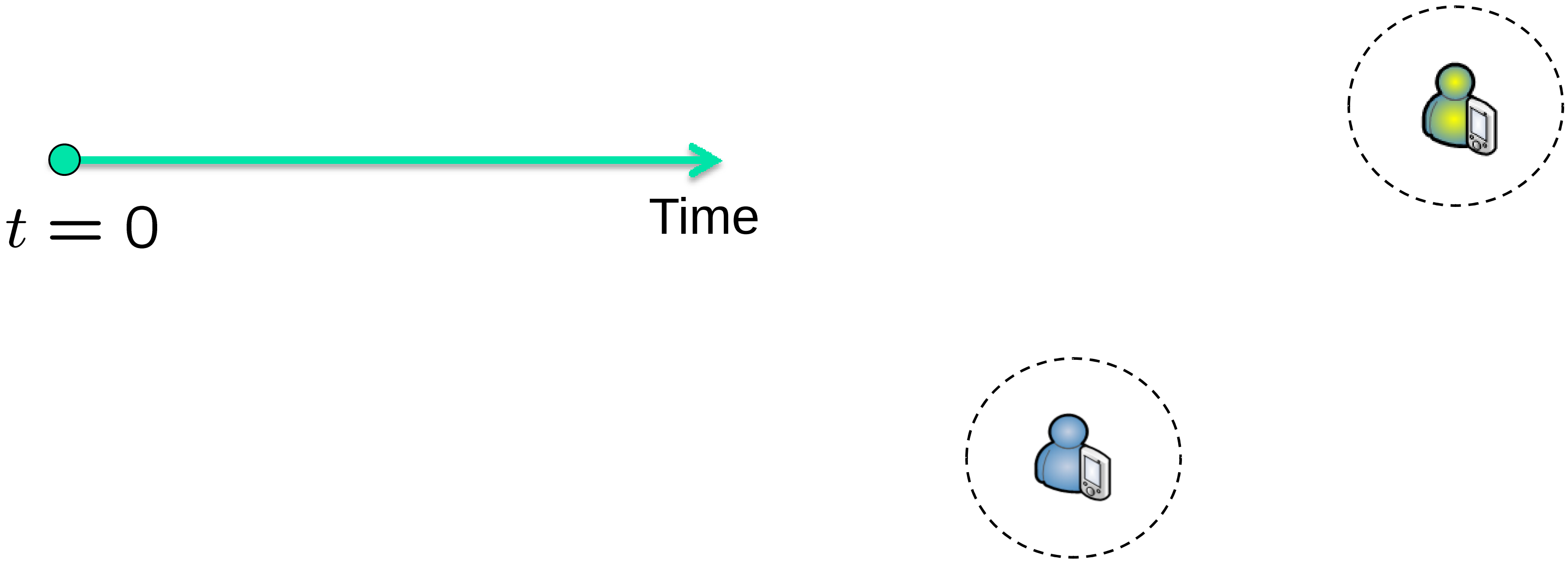

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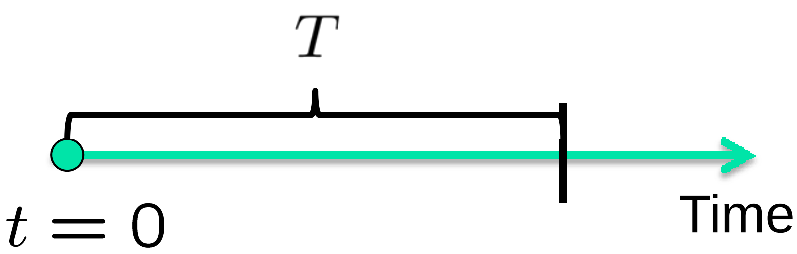
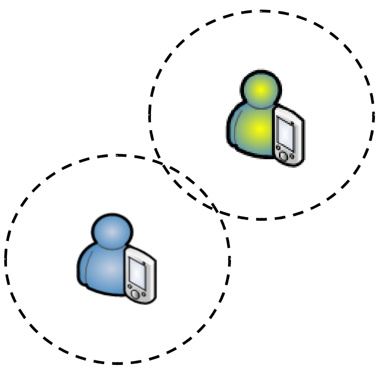




- **Inter-contact time:** how long two mobile nodes take to meet with each other again
- Need to know the characteristic of inter-contact time of each node pair

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 missing?

- Heterogeneity arises everywhere!
- Many empirical studies [1-6] have shown the existence of heterogeneity structures and their characteristics.
  - Make heterogeneous in contact patterns or dynamics for each node pair
  - Cannot be characterized by a pure Poisson process with same rate

- [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*.

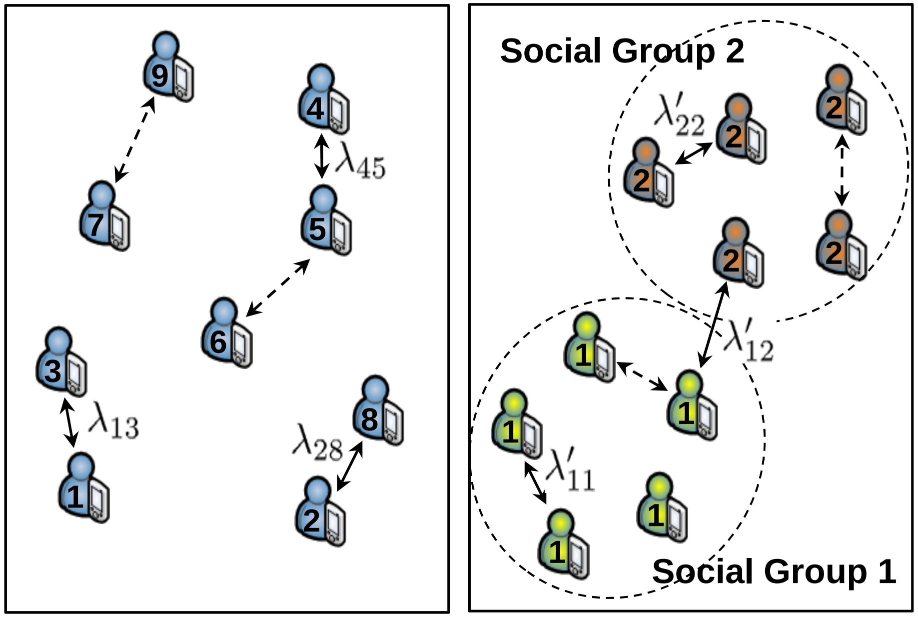
From Motivation to Our Work

- Heterogeneity structures have mainly used for the development of new mobility models, and empirically exploited in the design of new forwarding/routing algorithms.

- Typically ignored or marginalized when it comes to the rigorous performance analysis of forwarding algorithms

- Analytically investigate "how much benefit the heterogeneity in mobile nodes' contact dynamics can bring in the forwarding performance (if correctly exploited)?"

Heterogeneous Network 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)
- Capture social community structures
- Mathematically tractable

- [1] V. Conan, J. Leguay, and T. Friedman, "Characterizing pairwise inter-contact patterns in delay tolerant networks," in *Proc. of Autonomics '07*.
- [2] W. Gao, G. Li, B. Zhao, and G. Cao, "Multicasting in delay tolerant networks: a social network perspective," in *Proc. of ACM MobiHoc*'09.
- [3] C.-H. Lee and D. Y. Eun, "Heterogeneity in contact dynamics: helpful or harmful to forwarding algorithms in DTNs," in *Proc. of WiOpt'09*.

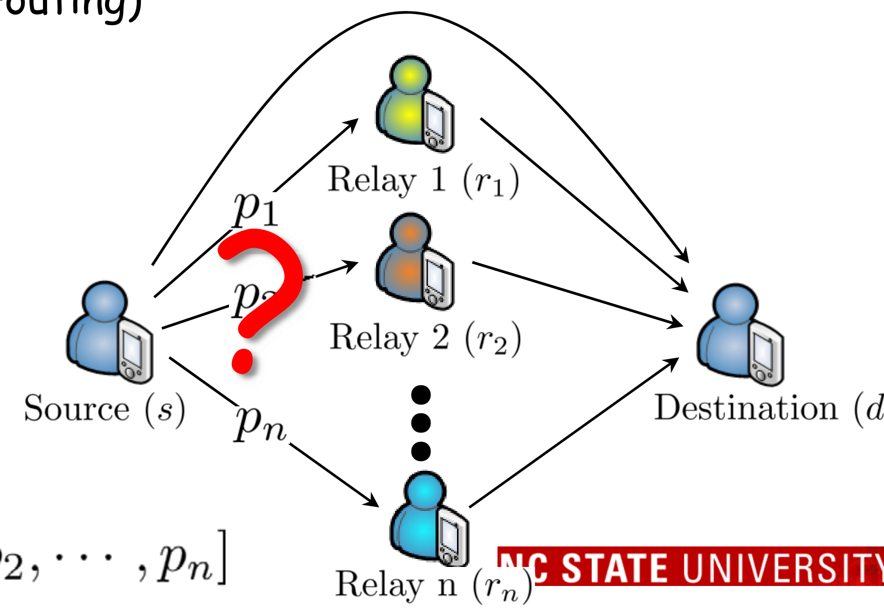
Problem Formulation

- A Class of Probabilistic Two-Hop Forwarding Policies w/ constraint
  - Total n+2 nodes (source, destination, *n* relay nodes)
  - Source forwards a message copy to each relay node with probability p_i upon encounter.
- Optimization Problem
  - Under the constraint on the number of message copies *K* (on average)
  - How to choose the forwarding probability p_i in minimizing the average message delivery delay? (Source routing)

$$\textbf{minimize} \quad \mathbb{E}\{D\}_{\vec{p}}$$

$$\textbf{subject to} \quad \sum_{i=1}^{n} p_i \le K,$$

$$\vec{p} = [p_1, p_2, \cdots, p_n]$$



Problem Formulation (cont'd)

- By solving the optimization problem, we will answer
- Question: how many message copies under heterogeneous setting are only enough to achieve an optimal delay performance predicted under homogeneous setting?
  - How much can we do better than expected under homogeneous setting, if the underlying heterogeneity is properly exploited?
  - Performance comparison (between hetero. and homo. settings) is done under the same overall average inter-contact time over all node pairs.

Solving Optimization Problem

- Optimization problem

$$\textbf{minimize} \quad \mathbb{E}\{D\}_{\vec{p}}$$

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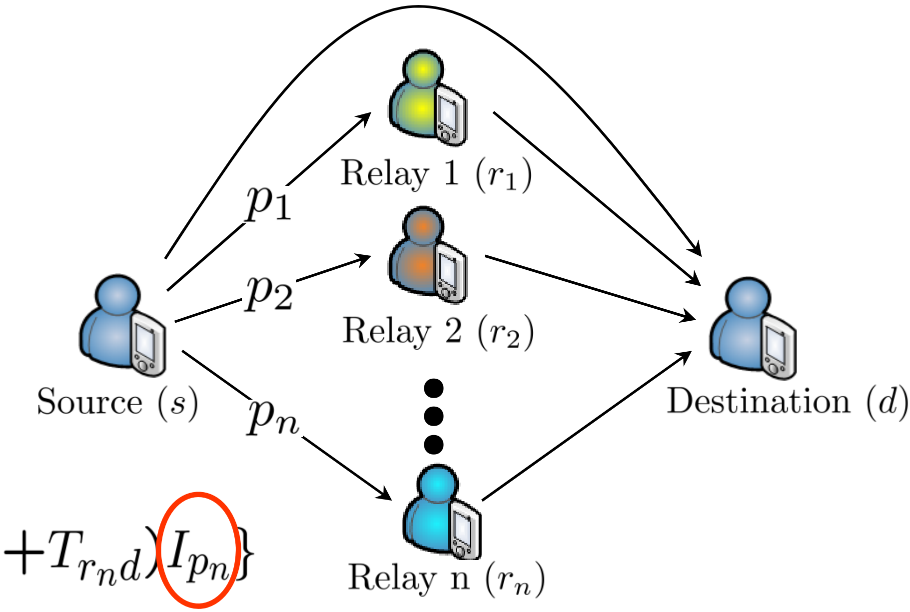


- Delay Analysis

$$D_{\vec{p}} = \min\{T_{sd}, (T_{sr_1}+T_{r_1d})I_{p_1}, \cdots, (T_{sr_n}+T_{r_nd})I_{p_n}\}$$

- Inter-contact time for a node pair (i,j): $T_{ij} \sim Exp(\lambda_{ij})$
- $I_{p_i} = \begin{cases} 1 & \text{if a relay node } r_i \text{ is chosen with prob. } p_i, \\ \infty & \text{otherwise.} \end{cases}$

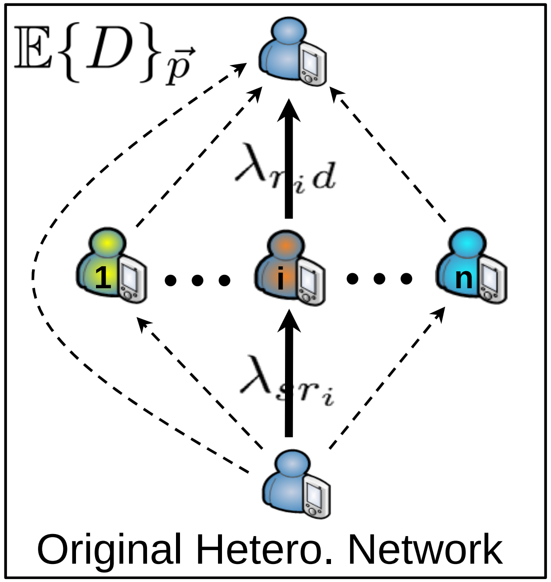
$$\Rightarrow \quad \mathbb{E}\{D\}_{\vec{p}} = \int_0^{\infty} \mathbb{P}\{T_{sd} > t\} \prod_{i=1}^{n} \left[p_i \mathbb{P}\{T_{sr_i} + T_{r_id} > t\} + (1 - p_i)\right] dt$$

Solving Optimization Problem (cont'd)

- Not a convex optimization problem
- Our approach
  - Derive an upper bound of the average delay for any forwarding policy $\vec{p}$
  - Still capture the underlying heterogeneity structure in mobile nodes' contact dynamics
  - Find a forwarding policy $\vec{p}^*$ which minimizes the delay upper bound derived
    - —Sub-optimal to the original optimization problem.
    - —However, a closed-form expression of its delay upper bound is obtained → Quantify the benefit of exploiting the underlying heterogeneity in the forwarding performance.

Solving Optimization Problem: Graphical Interpretation

- From delay analysis (delay upper bound) → Decomposition of an original heterogeneous network into *n* different partially homogeneous networks.



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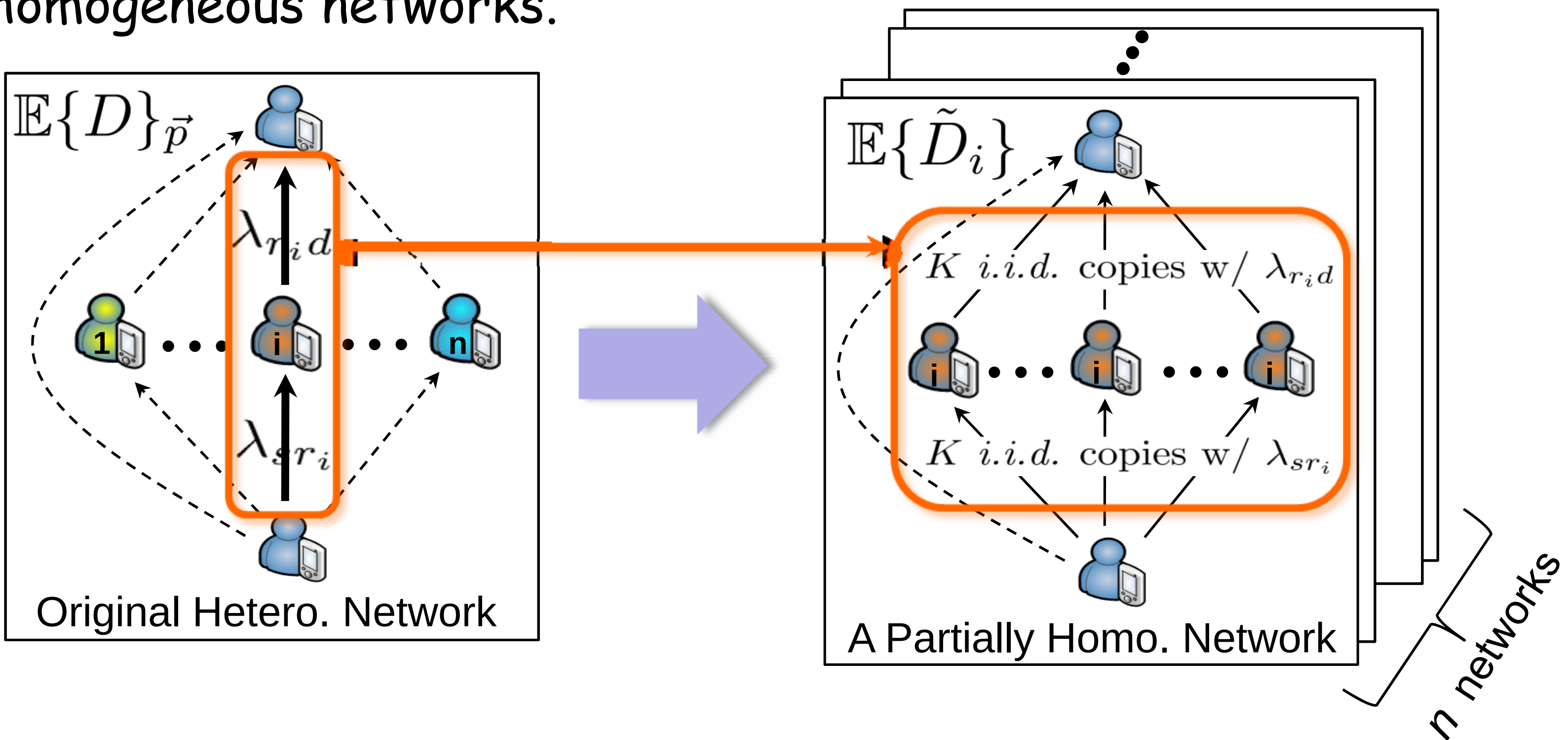


$$\mathbb{E}\{\tilde{D}_i\} = \begin{cases} \frac{1}{(\lambda_{r_i d} - \lambda_{s r_i})^K} \sum_{j=0}^{K} \binom{K}{j} \frac{(-\lambda_{s r_i})^j \lambda_{r_i d}^{K-j}}{\lambda_{sd} + j\lambda_{r_i d} + (K-j)\lambda_{s r_i}}, & \lambda_{s r_i} \neq \lambda_{r_i d} \\ \frac{1}{\lambda_{s r_i}} \sum_{j=0}^{K} \frac{K!}{(K-j)!(K+\lambda_{sd}/\lambda_{s r_i})^{j+1}} & \lambda_{s r_i} = \lambda_{r_i d}. \end{cases}$$

Solving Optimization Problem: Graphical Interpretation (cont'd)

- A forwarding policy $\vec{p}^*$ for a given constraint on # of message copies K
- $\mathbb{E}\{\tilde{D}_i\}$: a metric to indicate the quality of each relay path via relay node *i*
- Compute $\mathbb{E}\{\tilde{D}_1\}, \mathbb{E}\{\tilde{D}_2\}, \mathbb{E}\{\tilde{D}_3\}, \ldots, \mathbb{E}\{\tilde{D}_n\}$

$$\Rightarrow \boxed{\mathbb{E}\{\tilde{D}_{[1]}\} \leq \mathbb{E}\{\tilde{D}_{[2]}\} \leq \mathbb{E}\{\tilde{D}_{[3]}\} \leq \cdots \mathbb{E}\{\tilde{D}_{[K]}\}} \leq \cdots \leq \mathbb{E}\{\tilde{D}_{[n]}\}$$

$\vec{p}^*$

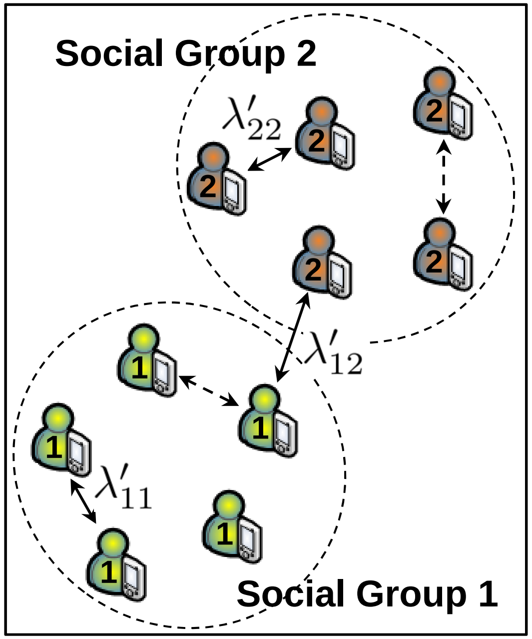
$$\Rightarrow \mathbb{E}\{D\}_{\vec{p}^*} \leq \prod_{l=1}^{K} \left[\mathbb{E}\{\tilde{D}_{[l]}\}\right]^{1/K}$$

Performance Gain of Exploiting Heterogeneity

- 22 nodes with two social groups (G_1 and G_2)
  - A special case of the heterogeneous model
- λ'_{ij} : a common contact rate between any member of G_i and G_j, where $i,j = 1,2$.
- Parameter Setting

$$\lambda'_{11} = 2\times10^{-4},\ \lambda'_{22} = 2\times10^{-5},\ \text{and}\ \lambda'_{12} = 10^{-4}$$

  - Mobile nodes in G_1 are more socially active than those in G_2
- For the corresponding homogeneous setting,
  - the average inter-contact time for any node pair is the same as the overall average inter-contact time over all node pairs in the heterogeneous setting

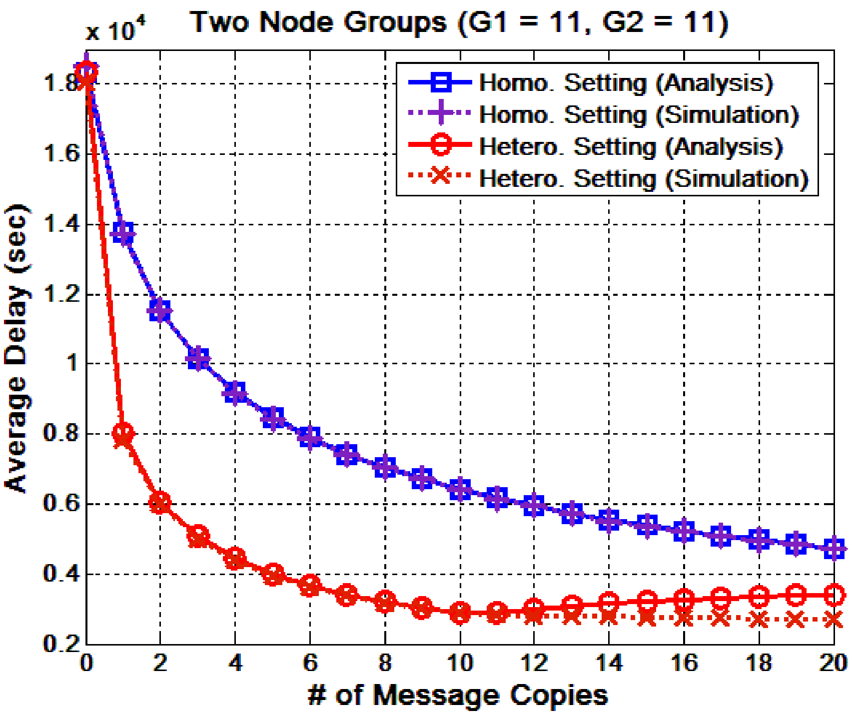


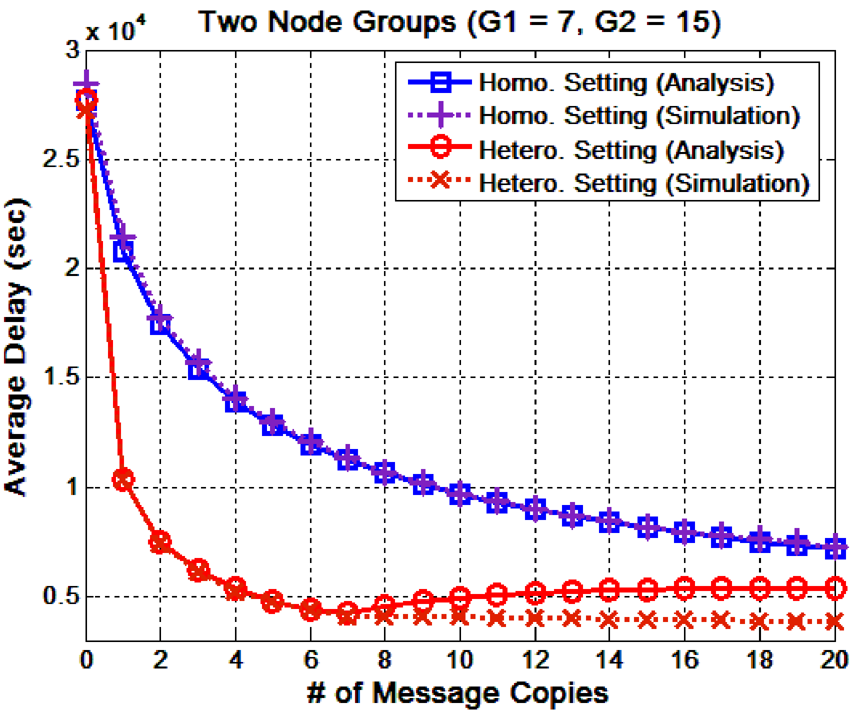
$$\bar{\mu} = \frac{2}{n(n-1)} \sum_{i=1}^{n} \sum_{j>i} \frac{1}{\lambda_{ij}},$$

where $n = 22$.

Performance Gain of Exploiting Heterogeneity (cont'd)

- Average delay for a uniform s-d pair achieved via the forwarding policy $\vec{p}^*$ per each given number of message copies (constraint) under hetero. and corresponding homo. settings.





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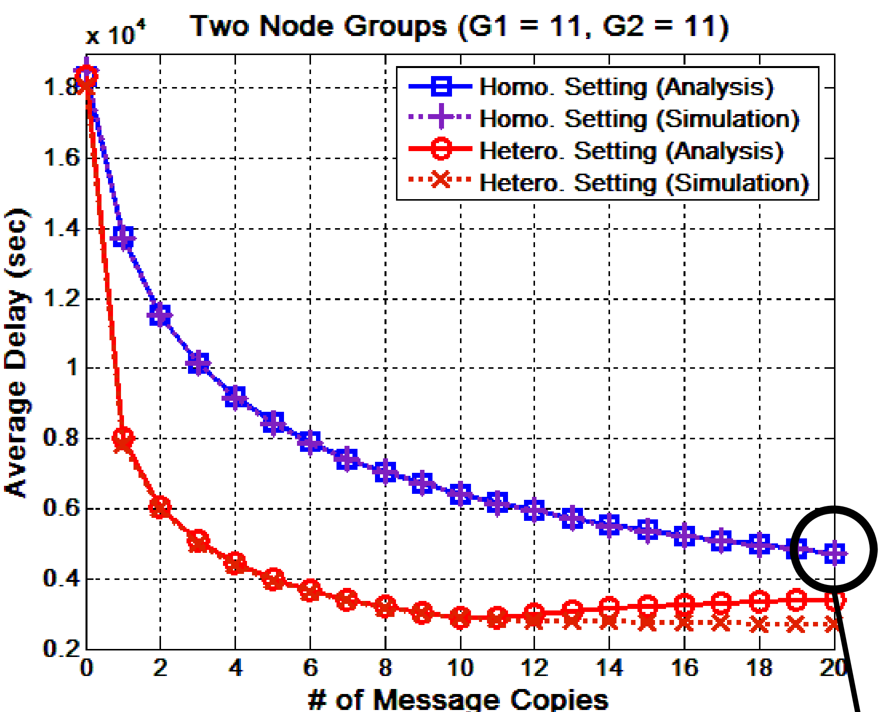

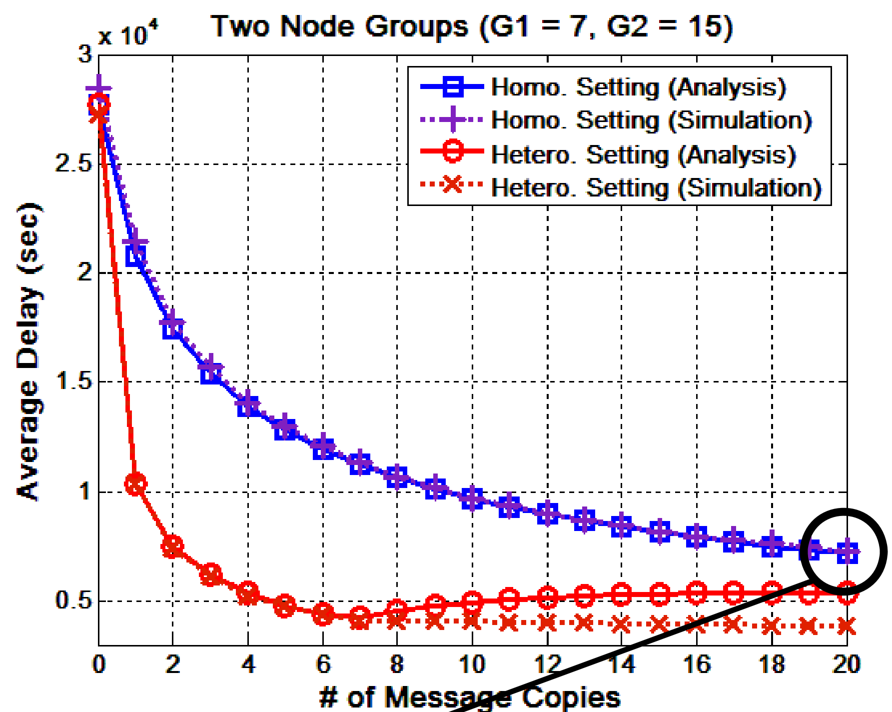

Optimal delay under homo. settings (achieved through unlimited message copies)

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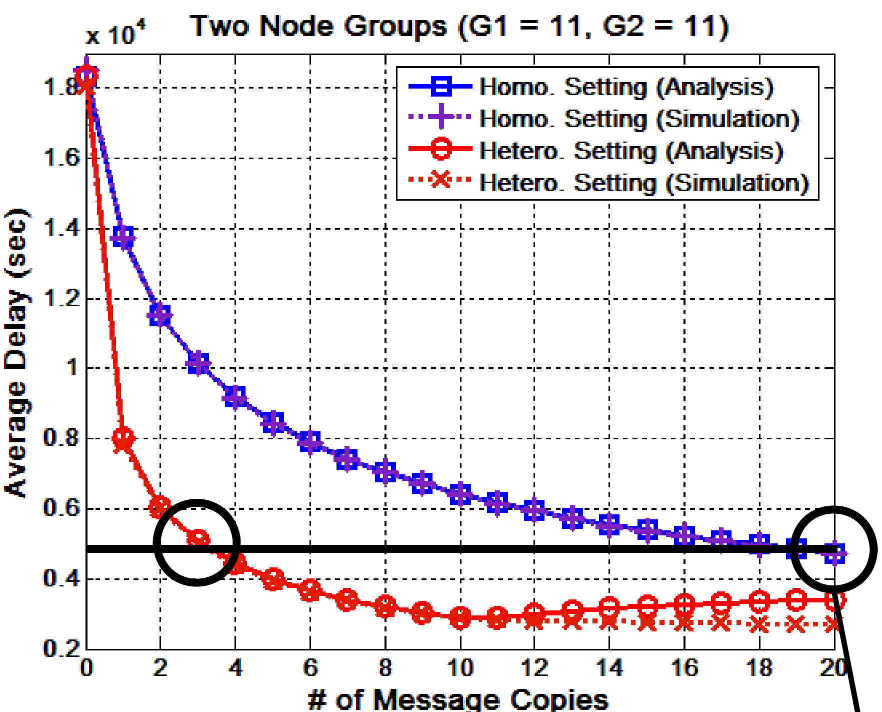

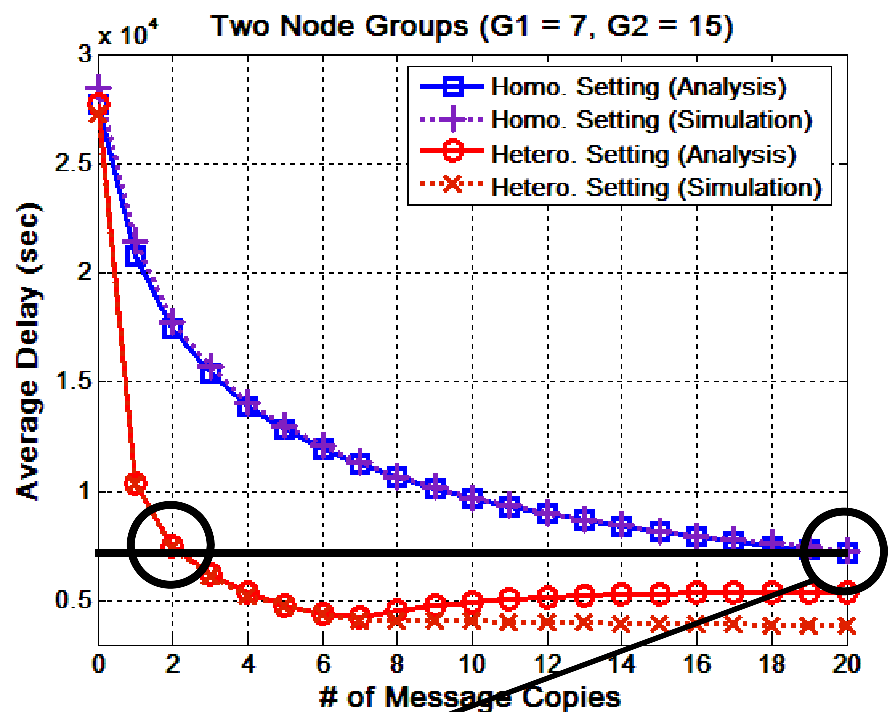

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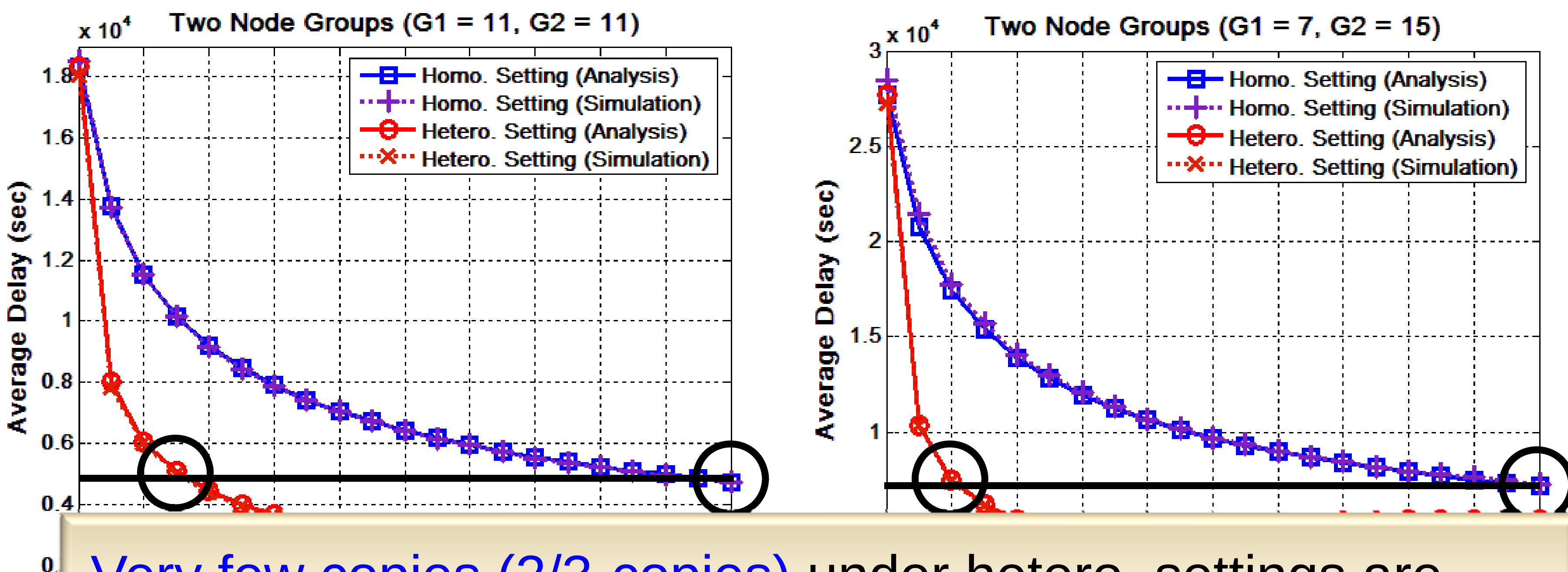

Very few copies (2/3-copies) under hetero. settings are enough to achieve the performance limit of any (two-hop) forwarding policies under homo. settings.

Performance Gain of Exploiting Heterogeneity (cont'd)

- A real Bluetooth contact trace, *Infocom'05* [1]
  - Contains 41 nodes' contact information over 3 days
- 22 nodes' contact information in the *Infocom'05* trace
  - Extract the average pairwise inter-contact time of all node pairs and use them under the heterogeneous model (for hetero. setting)
  - Also, use the overall average inter-contact time for the homo. setting.
- In the (event-driven) numerical simulation,
  - Random contacts of each node pair are generated according to a Poisson process with the extracted average pairwise inter-contact time for hetero. setting. Similarly, done for homo. setting.

- [1] A. Chaintreau, P. Hui, J. Crowcroft, C. Diot, R. Gass, and J. Scott, "Impact of human mobility on the design of opportunistic forwarding algorithms," in *Proc. of IEEE INFOCOM'06*.

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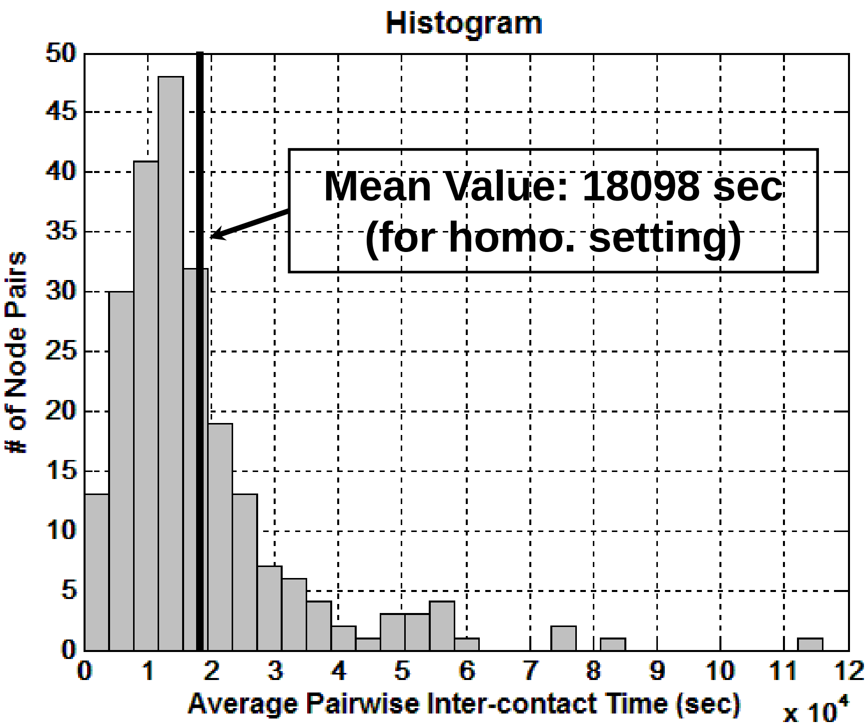

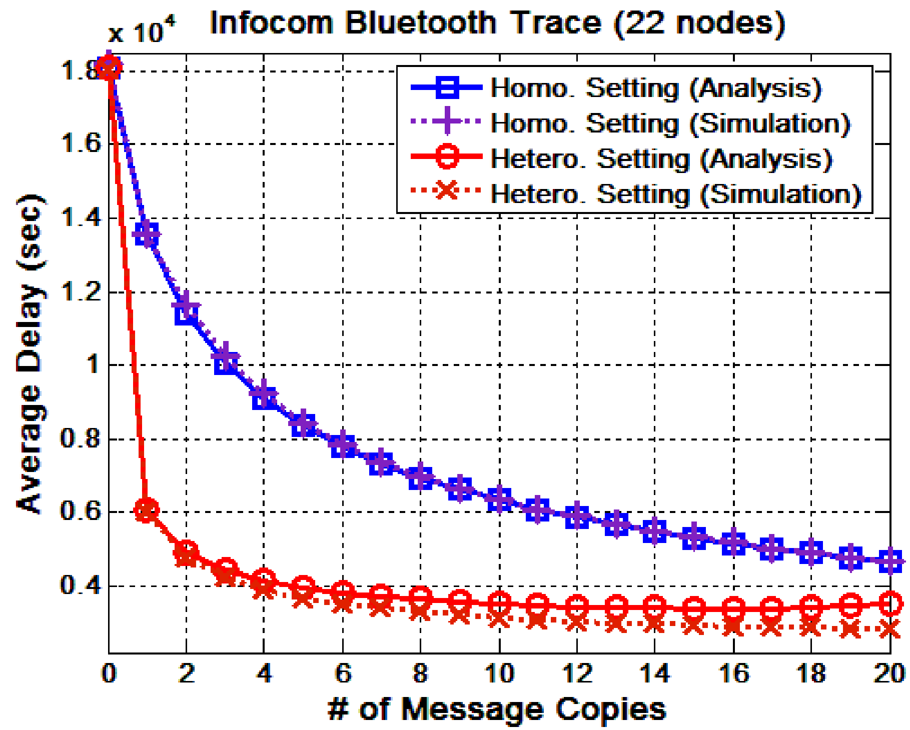

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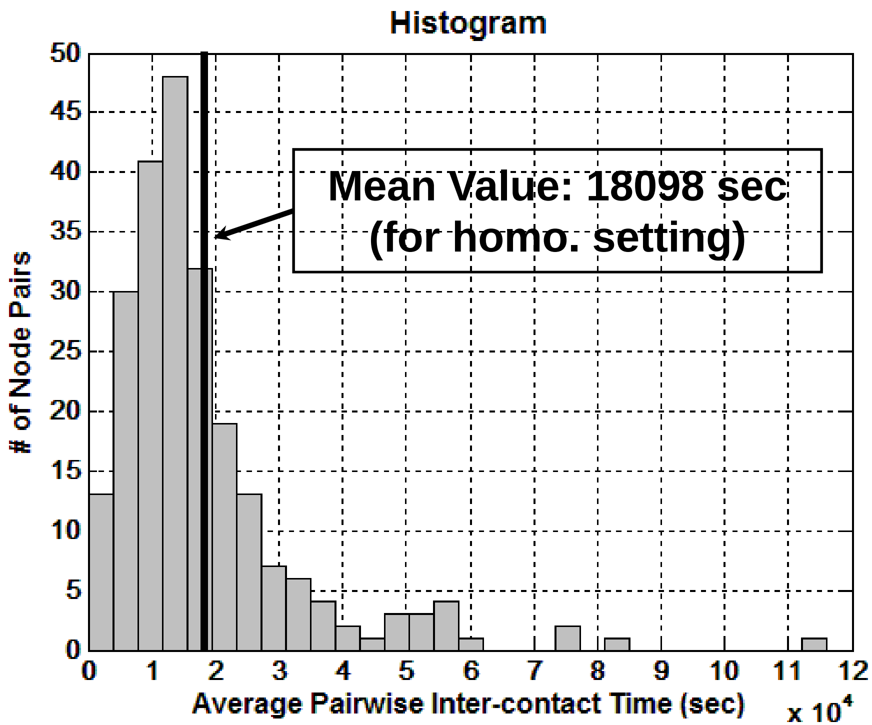

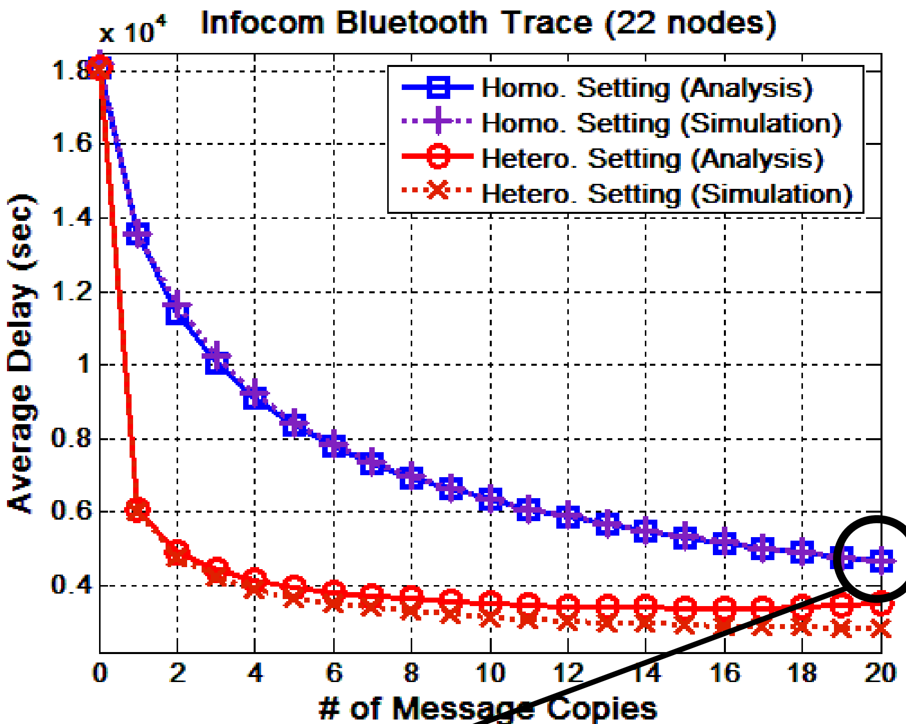

Optimal delay under homo. setting
(achieved through unlimited message copies)

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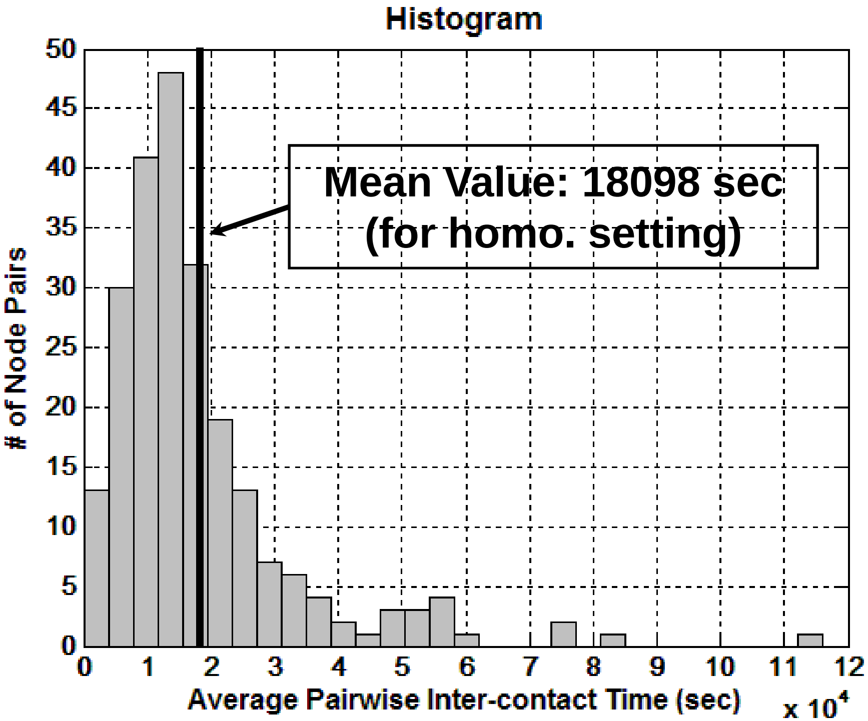

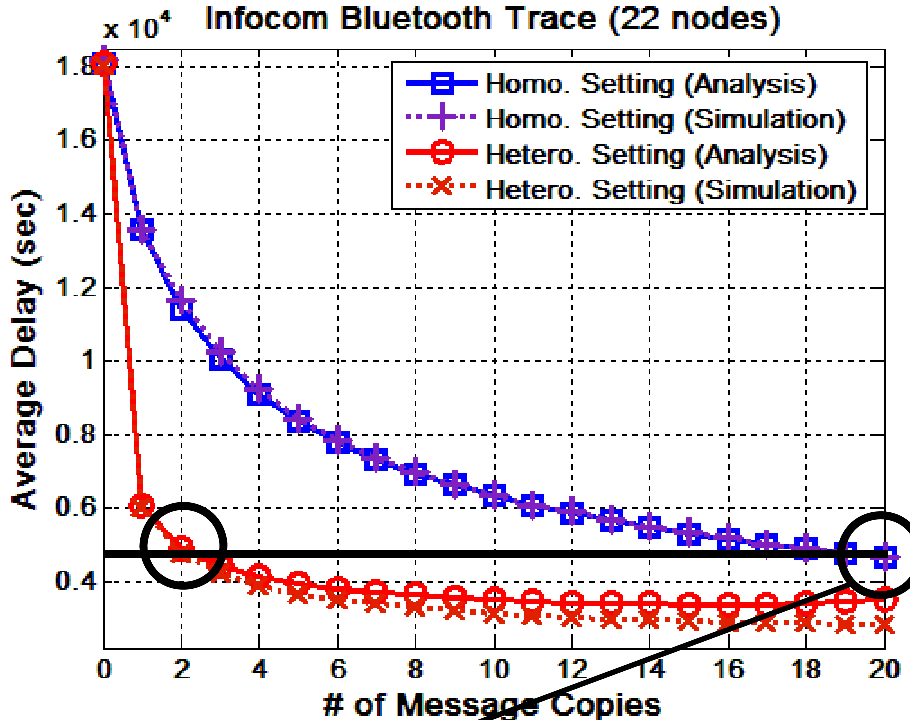

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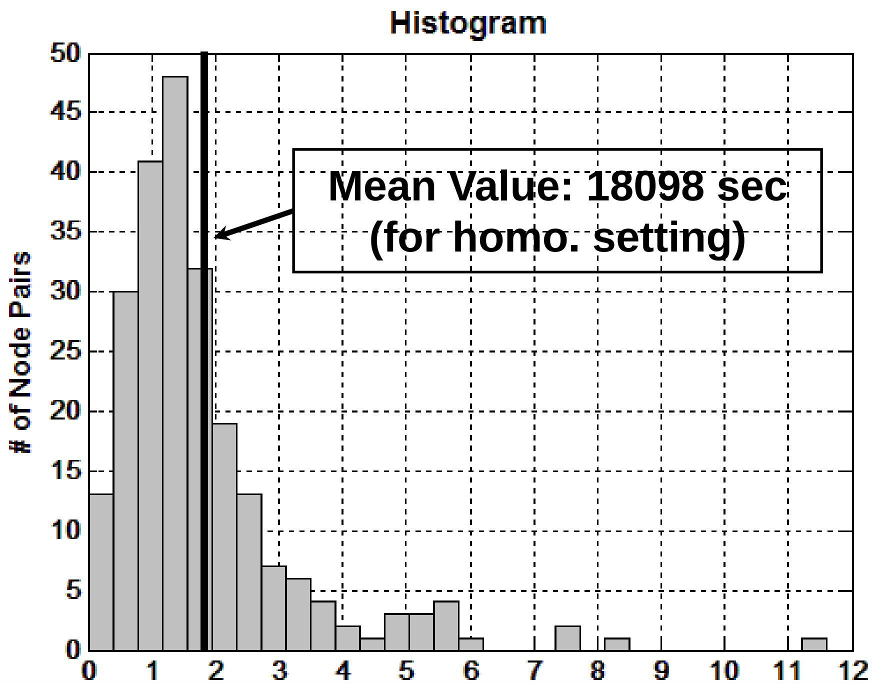

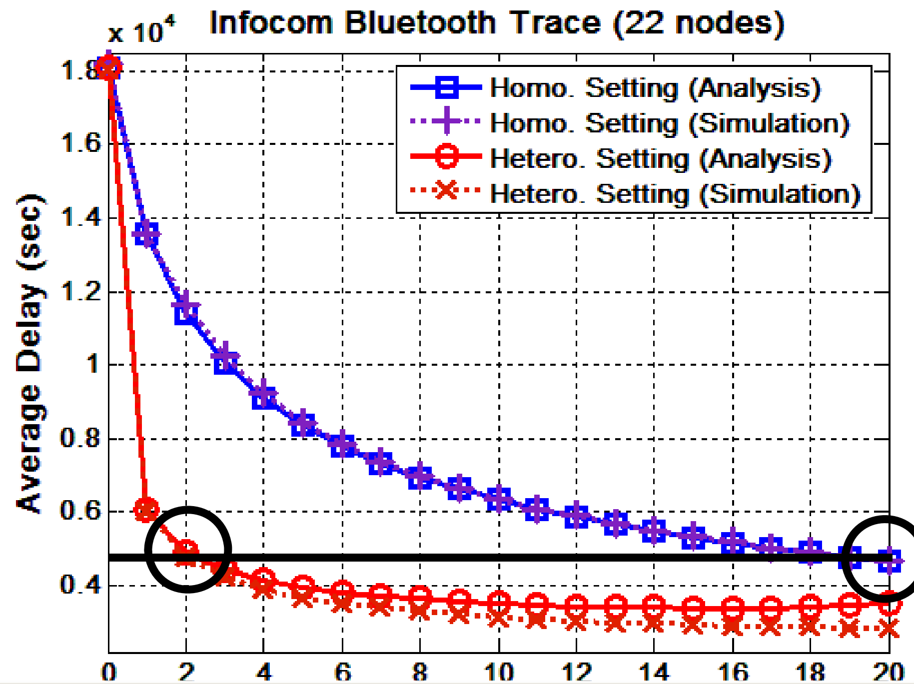

High level of Path Diversity → Significant Performance Gain

Conclusion

- Obtained a closed-form expression for the guaranteed delay bound of a (two-hop) forwarding policy per a given number of message copies.
  - Exploiting the underlying heterogeneity in mobile nodes' contact dynamics.
- Quantitatively showed performance gain through the guaranteed delay bound of the forwarding policy
  - Does not count the benefit of changing the relay paths on-the-fly upon encounter → Performance gain will be much higher than expected.
  - Cannot be captured in any existing analytical studies based on the homogeneous network model
- Complement the existing empirical studies on the design of forwarding/routing algorithms which exploit the underlying heterogeneity structure.

Thank You!!