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

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Chul-Ho Lee and Do Young Eun Dept. of ECE, North Carolina State University

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



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<u>An end-to-end path (in the normal definition) doesn't exist!</u> <u>However, message can be delivered eventually over *time*!!</u>





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







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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

<u>Pairwise</u> 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
- <u>Aggregate</u> 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.





- Many analytical studies [1-6] have used <u>"homogeneous</u> <u>model"</u>
  - ➤ 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 !!



- 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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#### 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 mobilityassisted 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*.







NCSU campus map













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







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







- 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

 $\rightarrow$  Individually (or socially) heterogeneous structure







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



- Use two representative heterogeneous network models mathematically tractable
  - 1. Individually heterogeneous network model [1-2]
  - 2. Spatially heterogeneous network model [3]
- How <u>heterogeneity in mobile nodes' contact dynamics</u> impact the performance of routing/forwarding algorithms in DTNs, along with <u>capturing the non-Poisson</u> <u>contact dynamics</u>?
- [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*.
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# *Individually* heterogeneous network model (Individual model)



#### **Model Description --**

- The inter-contact time distribution between two nodes (i,j) is exponential with  $\lambda_{ij}$
- Heterogeneity: different contact rate  $\lambda_{ij}$  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 intercontact time distribution is exponential with  $\beta_k$
- Heterogeneity: different contact rate  $\beta_k$  in each spatial cluster k
  - Assume q<sub>ij</sub> = q<sub>ji</sub> (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*.





The aggregate inter-contact time distribution under <u>individual model</u> → a weighted sum of exponentials (hyperexponential) [1]

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

■ <u>Proposition</u>: The pairwise inter-contact time distribution of a given node pair *i* under <u>spatial model</u> 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!!



- [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 – 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 intercontact 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**



- [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*.



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

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



# Results I – Average Delay

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

	Spatial vs. Homo.	Individual vs. Homo.
Direct Forwarding	$\mathbb{E}\{D_{sp}\} \ge \mathbb{E}\{D_{ho}\}$	$\mathbb{E}\{D_{in}\} = \mathbb{E}\{D_{ho}\}$
Multicopy Two-hop Relay	$\mathbb{E}\{D_{sp}\} \ge \mathbb{E}\{D_{ho}\}$	$\mathbb{E}\{D_{in}\} \le \mathbb{E}\{D_{ho}\}$



# Results I – Average Delay

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

$\{D_{ho}\}$
$\{D_{ho}\}$
}

The underlying heterogeneity structure captured in each heterogeneous model yields <u>a totally different delay performance</u>.
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# Results I – Spatial vs. Homo.

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

	Spatial vs. Homo.	Spatial Heterogeneity
Direct Forwarding	$D_{sp} \ge_{st} D_{ho}$	$\begin{array}{c} \text{Site 1}  q_{21} \\ \\ q_{12} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$
Multicopy Two-hop Relay	$D_{sp} \ge_{st} D_{ho}$	

Then,  $D_{sp}$  is stochastically larger than  $D_{ho}$  $\mathbb{P}\{D_{sp} > t\} \ge \mathbb{P}\{D_{ho} > t\}$  for all  $t \ge 0 \implies \mathbb{E}\{D_{sp}\} \ge \mathbb{E}\{D_{ho}\}$ 

# Results I – Individual vs. Homo.

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





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

Snatial ve Home Individual ve Hon

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





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

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

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



- 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!!

