Contact-based Metrics and Performance Implications in Mobile Ad-hoc Networks

Do Young Eun

Dept. of Electrical and Computer Engineering

North Carolina state University

June 2008

Disclaimer

- Collaboration with Han Cai, a PhD student at NCSU
- This talk is based on our recent two papers in
  - [1] Han Cai and Do Young Eun, "Crossing Over the Bounded Domain: From Exponential to Power-law Inter-meeting Time in MANET," in **ACM MobiCom'07**, Montreal, Canada, Sept. 2007 **(Best Student Paper Award)**
  - [2] Han Cai and Do Young Eun, "Stochastic Anatomy of Inter-meeting Time Distribution under General Mobility Models," in **ACM MobiHoc'08**, Hong Kong SAR, China, May 2008
- Papers and more details available at http://www4.ncsu.edu/~dyeun

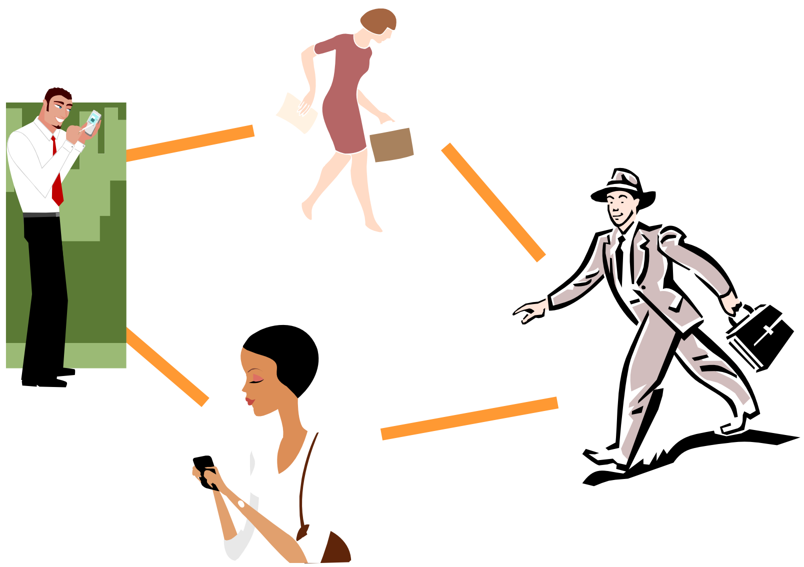
Content

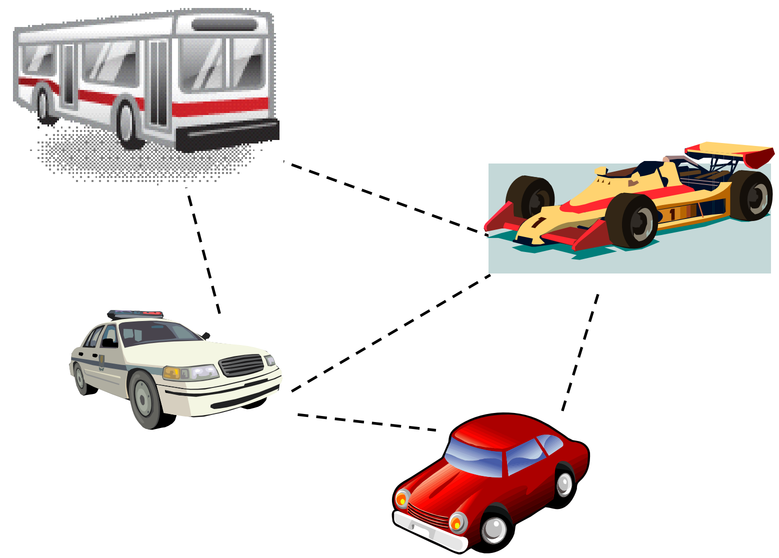
- **Introduction**
  - **Background: MANET, mobility models, contact-based metrics**
  - Motivation
- Crossing over the bounded domain: From exponential to power-law inter-meeting time
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

Mobile Ad-hoc Network (1)

- A type of self-configuring wireless ad-hoc network
  - Mobile nodes
  - Wireless communication devices

Mobile Ad-hoc Network (2)



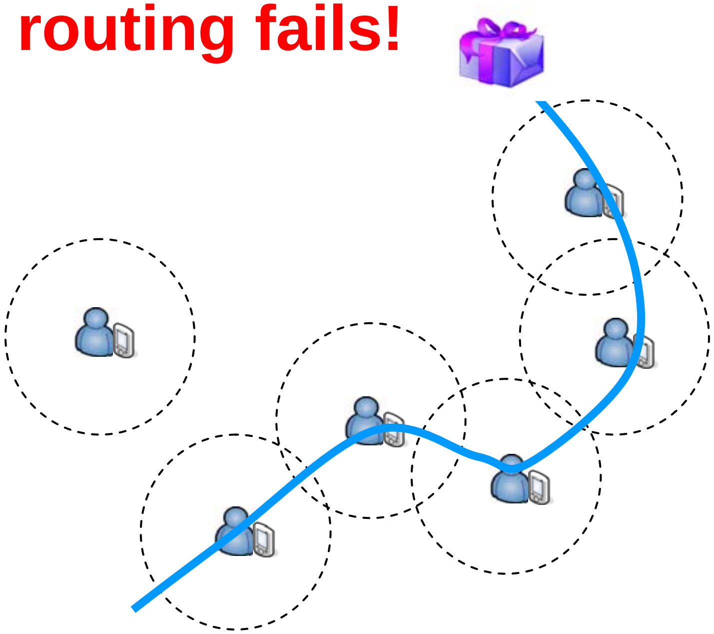


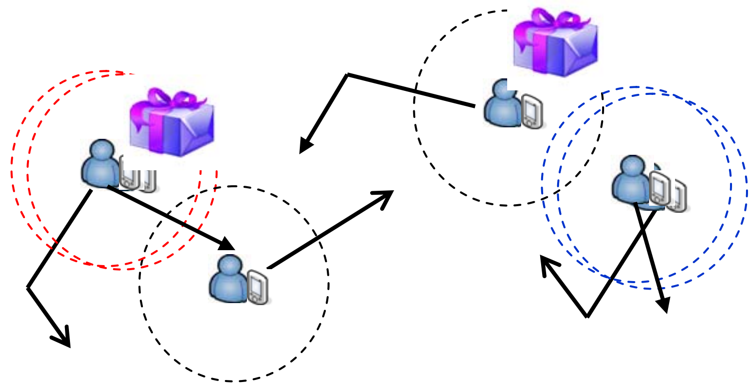
- Pocket Switch Network [1]
- Vehicle Ad-hoc Network [2]

- [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 *IEEE INFOCOM*, Barcelona, SPAIN, 2006.
- [2] John Burgess, Brian Gallagher, David Jensen, and Brian Neil Levine, “Maxprop: Routing for vehicle-based disruption-tolerant networks”, in *IEEE INFOCOM*, Barcelona, SPAIN, August 2006.

Mobile Ad-hoc Network (3)

Intermittently connected – conventional path-based routing fails!

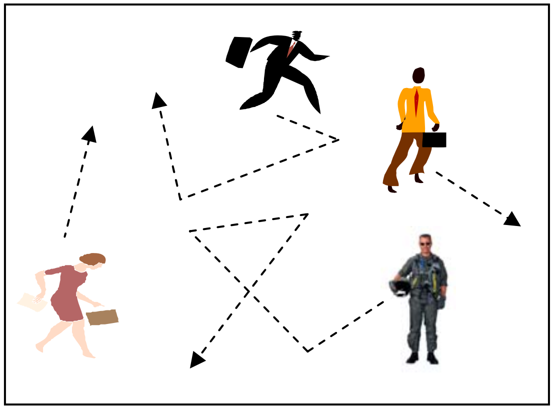




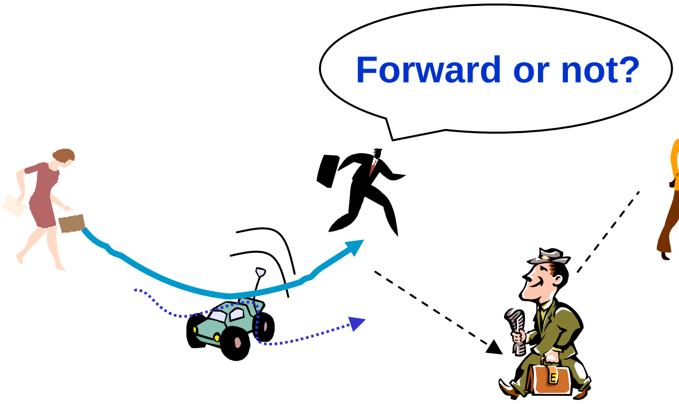
- Low mobility compared to packet transmission session
- High density ensures path existence

- **Low density**: conventional path fails
- **High mobility** compared to packet transmission session

Mobility, Forwarding, Performance

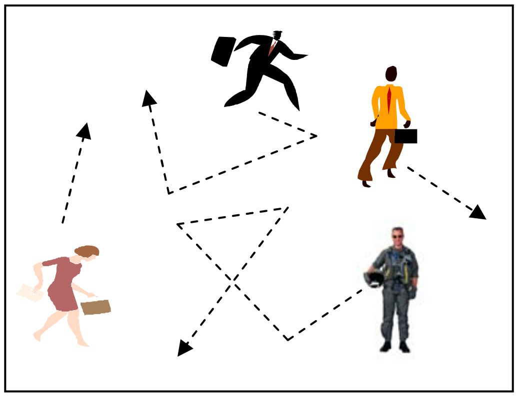


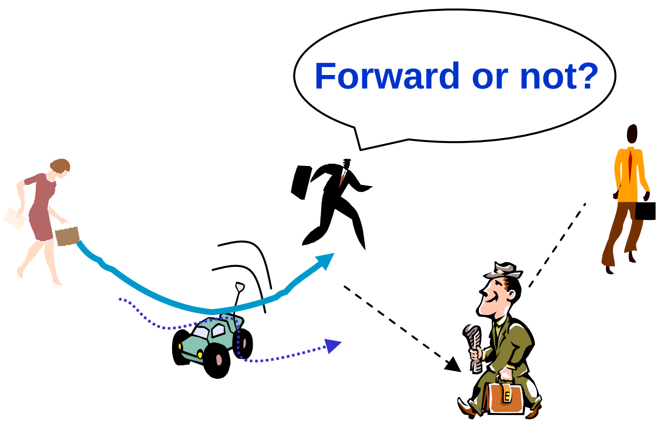
Random Mobility Pattern



Forwarding Strategy

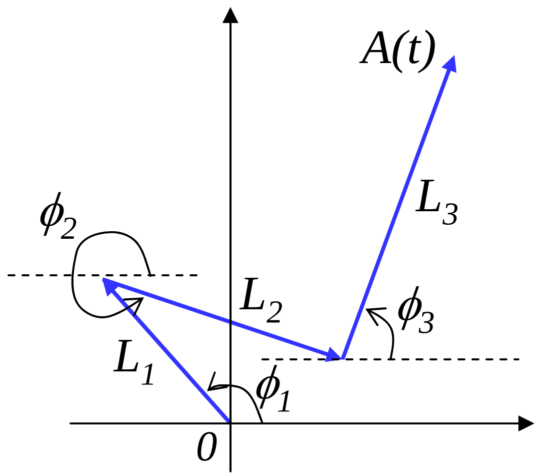
Mobility, Forwarding, Performance

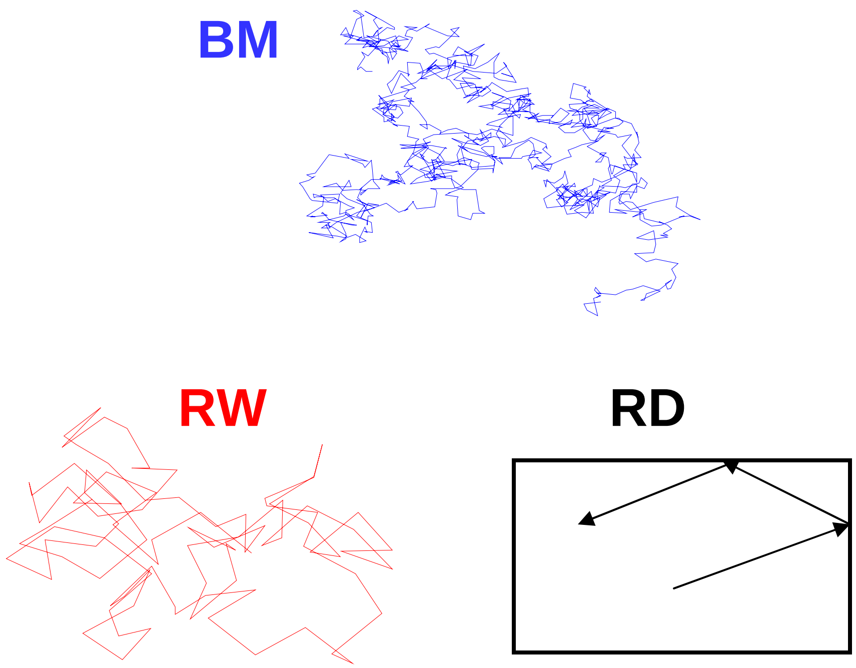




- Capacity
- Delay
- # of copies/pkt
- ……

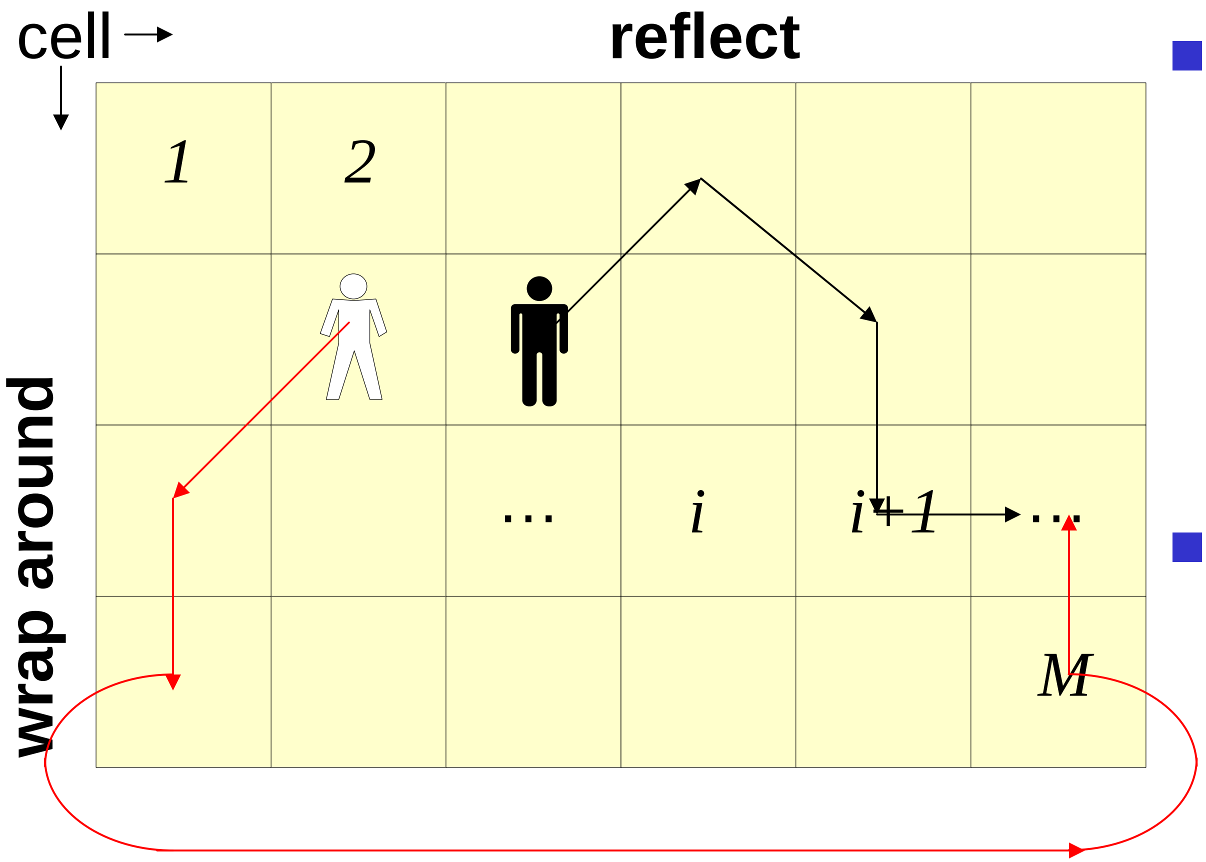
Mobility: Isotropic Random Walk model





- Isotropic Random Walk (IRW) models: BM, RW, RD, etc.
  - Angle: uniform
  - Step length: constant, exponential, uniform, etc.

Mobility: Discrete Random Walk (MC)



- Markov Chain RWM: transition matrix

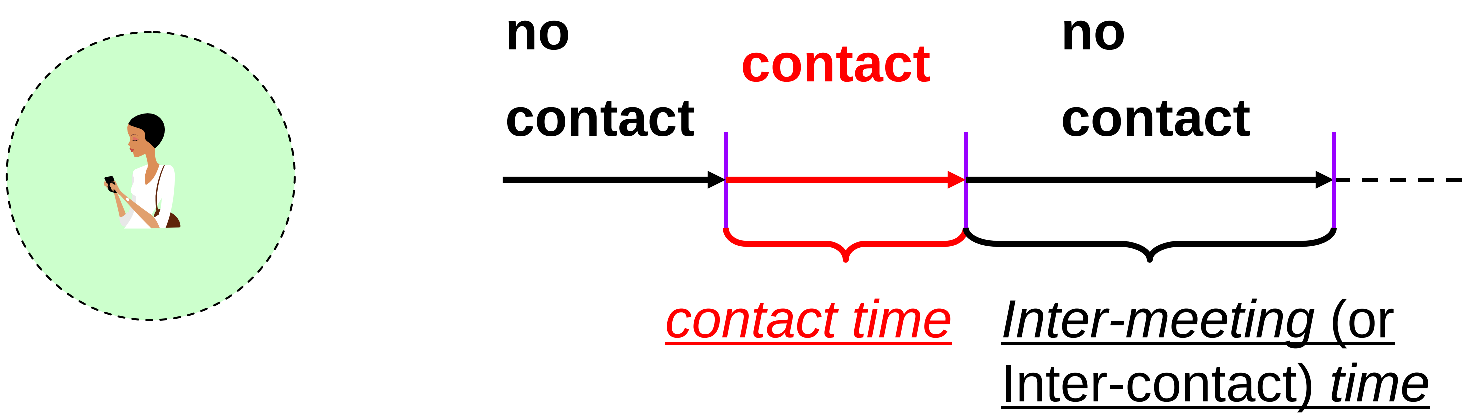
$$P = \{ p_{ij} \},$$

prob. of jumping from cell i to j

- Boundary behavior
  - Reflect
  - Wrap around

- Two node meet if and only if they are in the same cell

Mobility-Induced Metrics



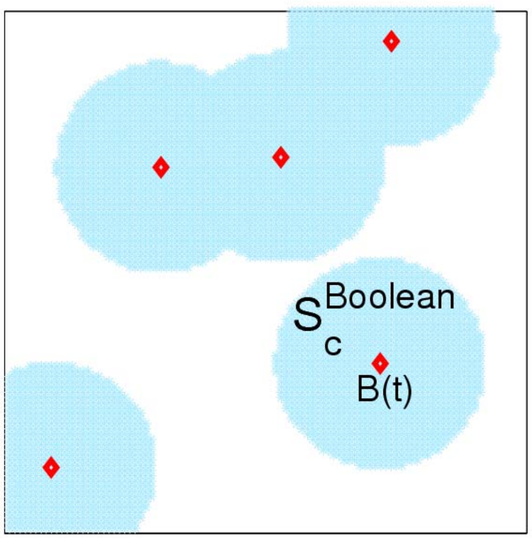
- Effect of mobility model on system performance → through mobility-induced metrics
  - Contact time, inter-meeting (or inter-contact) time, etc.

- F. Bai, N. Sadagopan, and A. Helmy, “Important: A framework to systematically analyze the impact of mobility on performance of routing protocols for ad-hoc networks,” in *IEEE INFOCOM* 2003.

How to define “Contact”? -- Interference Models

Boolean

$$\|A(t) - B(t)\| \leq d$$



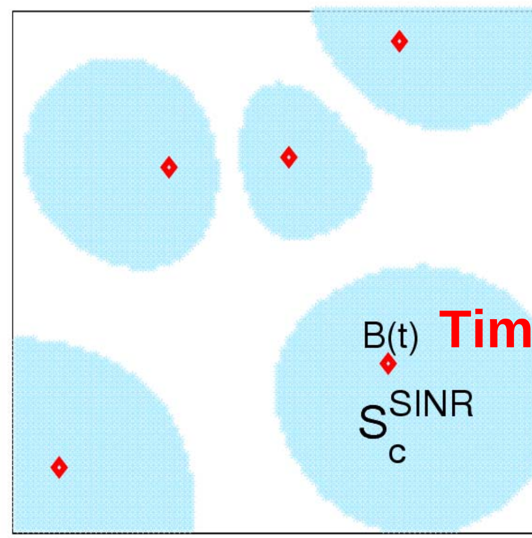
SINR

Path loss coefficient

$$\frac{P_A\|A(t) - B(t)\|^{\alpha}}{N_0 + \sum_{i=1}^{N} P_i\|M_i(t) - B(t)\|^{\alpha}} \geq \gamma_0$$

Noise power level

min. SINR required



Time varying

- Interference models: Distance-based; SINR based, etc.
  - P. Gupta and P.R. Kumar, “The capacity of wireless networks,” *IEEE Transactions on Information Theory*, 2000.

Content

- **Introduction**
  - Background: MANET, mobility models, contact-based metrics
  - **Motivation**
- Crossing over the bounded domain: From exponential to power-law inter-meeting time
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

Exponential Inter-meeting Time

- **Assumed** for tractable analysis

$$\boxed{\mathbb{P}\{T_I > t\} \sim e^{-ct}}$$

  - Delay-capacity tradeoff [1, 2]
  - Forwarding algorithm performance analysis [3, 4]
  - and many more….
- **Supported by**
  - Numerical simulations based on mobility model (RWP) [5]
  - Theoretical result to upper bound first/second moment [6] using BM

[1] Grossglauser, M., and Tse, D. N. C. “Mobility increases the capacity of Ad Hoc wireless networks”, *IEEE/ACM Transactions on Networking*, 2002.

[2] Sharma, G., Mazumdar, R., and Shroff, N. B., “Delay and Capacity Trade-offs in Mobile Ad Hoc Networks: A Global Perspective,” in *IEEE INFOCOM* 2006.

[3] T. Spyropoulos, K. Psounis, and C. Raghavendra, “Efficient Routing in Intermittently Connected Mobile Networks: The Multi-Copy Case,” in *IEEE/ACM Transactions on Networking*, Feb. 2008.

[4] X. Zhang, G. Neglia, J. Kurose, and D. Towsley, “Performance Modeling of Epidemic Routing,” *Computer Networks*, 2007.

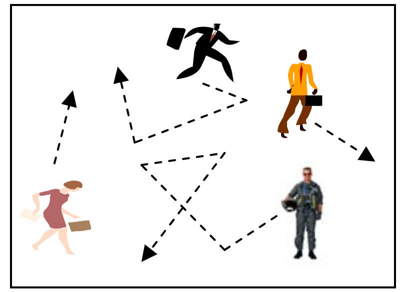
[5] Groenevelt, R., Nain, P., and Koole, G., “Message delay in MANET,” in *ACM SIGMETRICS*, 2004.

[6] Sharma, G., and Mazumdar, R. “On achievable delay/capacity trade-offs in Mobile Ad Hoc Networks,” *WiOpt*, 2004.

Exponential Assumption: Enabler of “Everything”…

$$\mathbb{P}\{T_I > t\} \sim e^{-ct}$$

Exponentially distributed
Inter-meting time of a pair



i.i.d. mobile nodes

[Poisson contact with rate λ among “all” mobile nodes]

- Poisson contact across time and space
  - “Memoryless” → no need to “remember” when was the last time of contact
  - You are likely to meet <u>anybody at any time instant</u> “regardless” of the past experience
  - Only “current status” matters (# of nodes having the packet in question, etc)
- Heavily adopted in almost all theoretical work so far
  - Capacity-delay tradeoff in mobile ad-hoc networks
  - Markovian analysis of forwarding/routing algorithms

But …

$$\mathbb{P}\{T_I > t\} \sim t^{-\alpha}$$

- **Recently discovered: Power-law [1, 2]**

Effect of power-law on system performance [1]

"… If $\alpha < 1$, none of these algorithms, including flooding, can achieve a transmission delay with a finite expectation…."

- [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 *IEEE INFOCOM*, Barcelona, SPAIN, 2006.
- [2] Hui, P., Chaintreau, A., Scott, J., Gass, R., Crowcroft, J., and Diot, C., "Pocket switched networks and the consequences of human mobility in conference environments," in *WDTN-05*.

Power-law Inter-meeting Time

Recent studies on power-law (selected)

- Call for new mobility models [1]
  - Use 1-D random walk model to produce power-law inter-meeting time [2]
- Call for new forwarding algorithms [3]

- [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 *IEEE INFOCOM*, Barcelona, SPAIN, 2006.
- [2] Boudec, J. L., and Vojnovic, M. “Random Trip Tutorial,” in *ACM MobiCom Tutorial*, 2006.
- [3] Lindgren, A., Diot, C., and Scott, J. “Impact of communication infrastructure on forwarding in pocket switched networks,” in *SIGCOMM workshop on Challenged networks*, 2006

Our Work

Key questions:

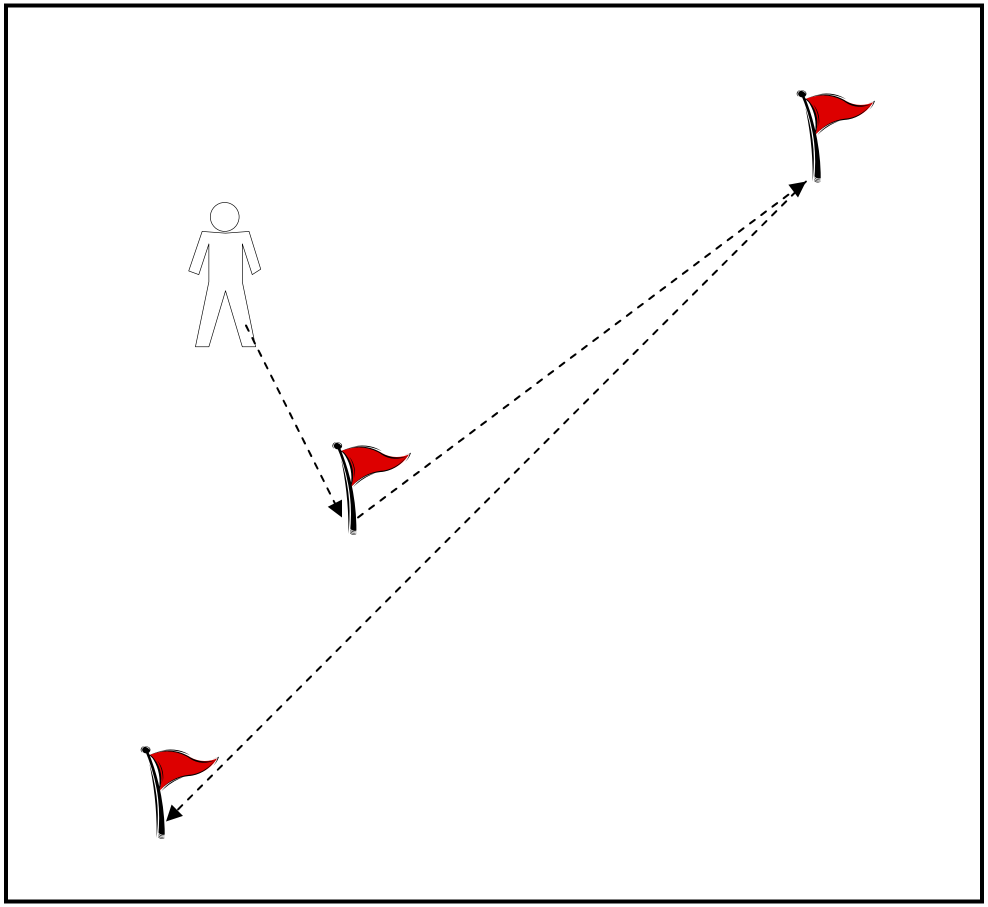
- What's the fundamental reason for the exponential & power-law behavior?
- What's the effect of general mobility patterns on system performance when the inter-meeting time is not purely exponential?

We provide answers to these questions !!

Content

- Introduction
- **Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time**
  - **Inter-meeting time with exponential tail**
  - From exponential to power-law inter-meeting time
  - Scaling the size of the space
  - Simulation
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

Random WayPoint Model



- RWP
  - Zero pause time
  - Random (light-tail) pause time
  - Independent pair of nodes
  - Boolean interference model

RWP with zero pause time

Proposition 1: Under zero pause time, there exists constant $c > 0$ such that

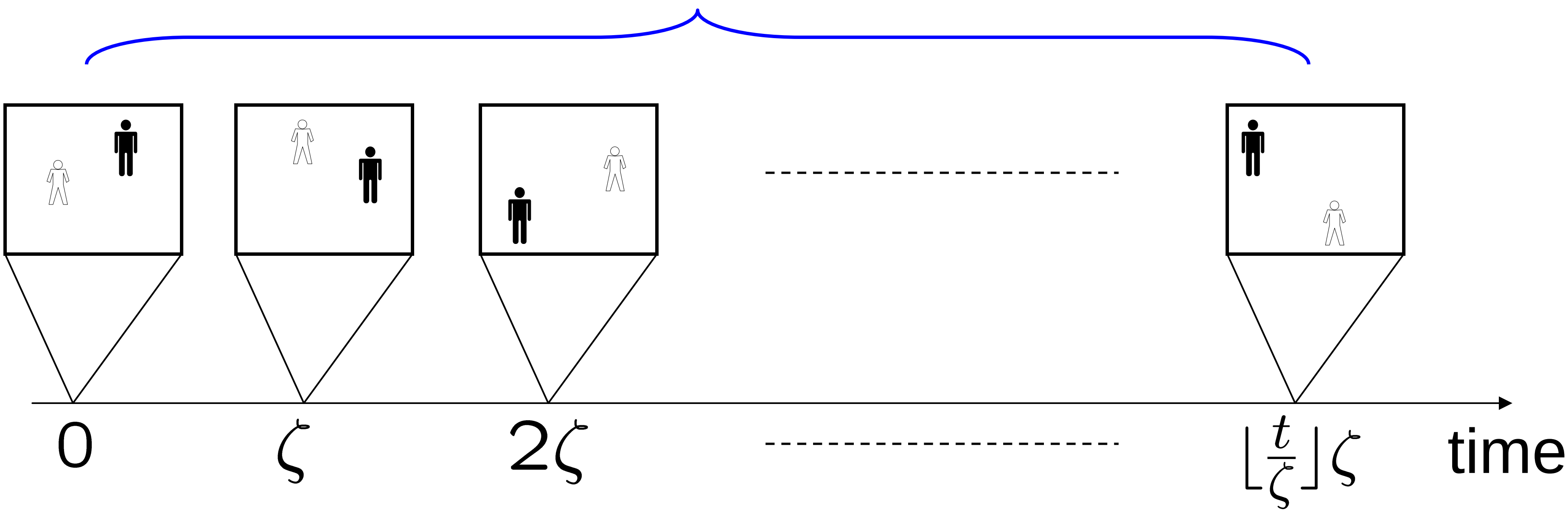
$$\boxed{P\{T_I > t\} < e^{-ct},}$$

for all sufficiently large *t*.

- Proposition 1 is also true for “bounded” pause time case.

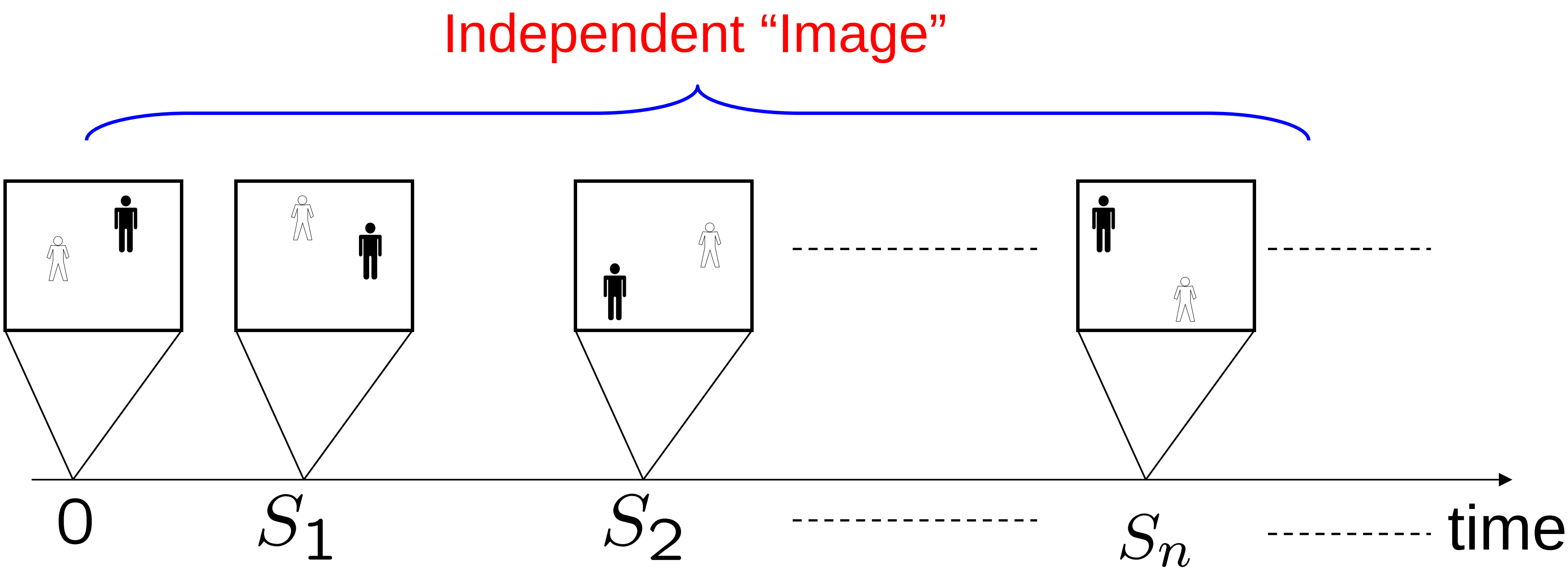
Proof sketch for Proposition 1

Independent “Images” (snapshot of node positions)



- Over duration of [0, t]
  - # of independent “images” = O(t)
  - Each “image”: P {not meeting} < c < 1

Random Pause Time: Difficulty



- Possibly infinite pause time
  - Impossible to get periodic independent images
  - Can we still get O(t) independent images?

RWP with random pause time

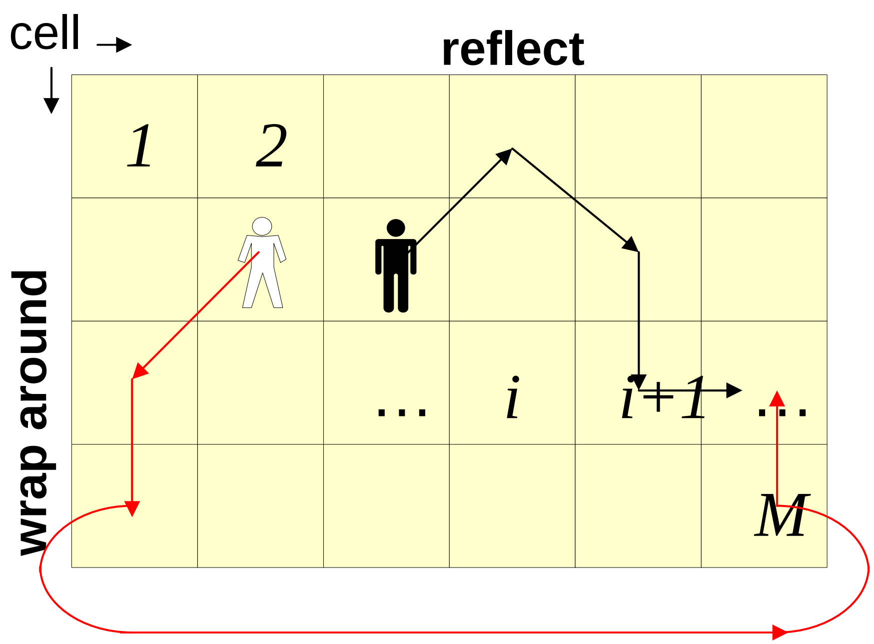
Theorem 1: Under random pause time, there exists constant $c > 0$ such that

$$\boxed{P\{T_I > t\} < e^{-ct},}$$

for all sufficiently large *t*.

- Proposition 1 is extended to random pause time case, i.e., the pause time may be infinite.
  - Condition: the pause time has finite moments
- First formal proof for the exponential tail behavior of inter-meeting time CCDF

RWM: exponential inter-meeting



- Markov Chain RWM: transition matrix $P = \{p_{ij}\},$

  prob. of jumping from cell *i* to *j*

- Boundary behavior
  - Reflect
  - Wrap around

Theorem 2: Two independent nodes move according to the RWM. Then, there exists constant $\gamma > 0$ such that

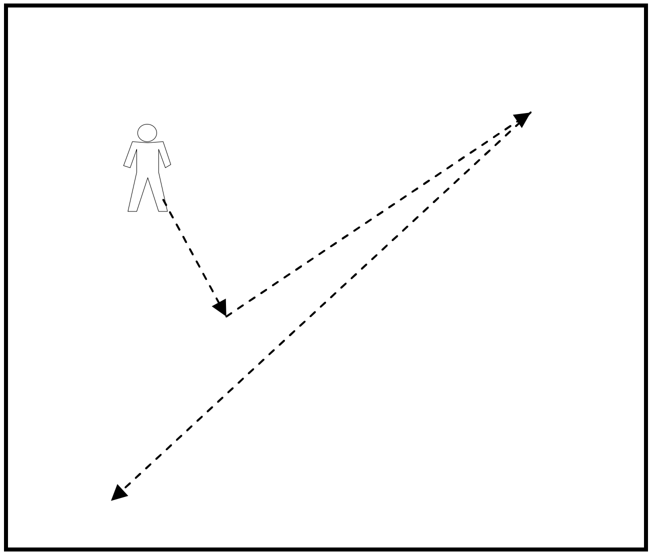
$$\boxed{P\{T_I > t\} \le e^{-\gamma t},}$$

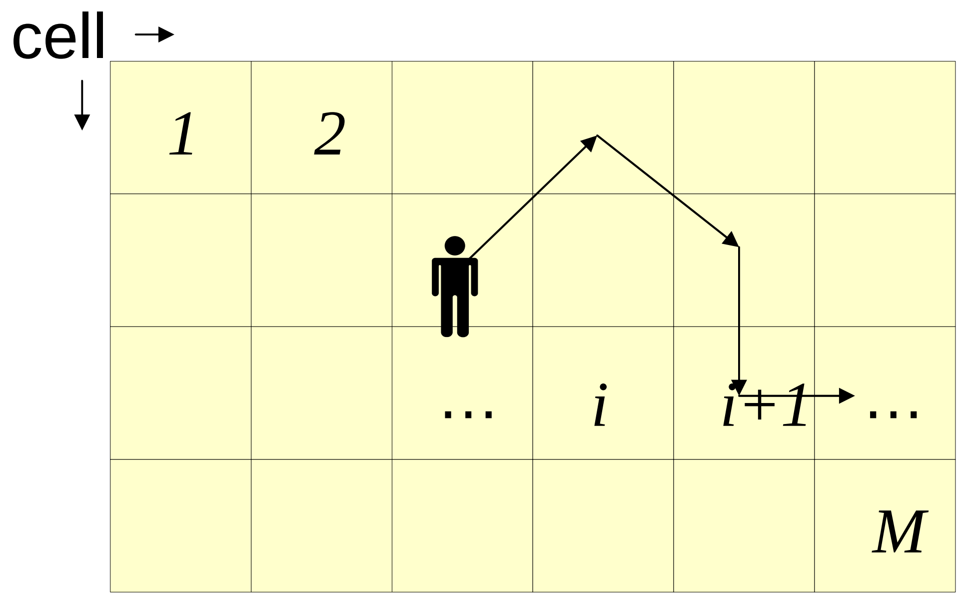
for all sufficiently large *t*.

Content

- Introduction
- **Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time**
  - Inter-meeting time with exponential tail
  - **From exponential to power-law inter-meeting time**
  - Scaling the size of the space
  - Simulation
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

Cause of Exponential Tail





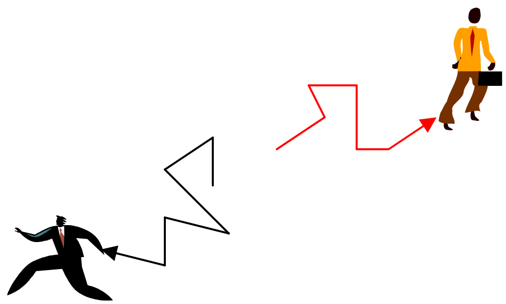
What is common in all these models?

Cause of Exponential Tail

Finite Boundary!!!

- “**Boundary**” is incorporated in the definition.
  - RWM: wrapping or reflecting boundary behavior
  - RWP: boundary concept inherited in model definition (destination for each jump is uniformly chosen from a bounded domain)
  - Virtual boundary
    - Intention of returning back to some locations regularly
    - Intention of being with others (mobile groups)
  - O(1) communication range on a finite domain = finite number of states → key to the exponential tail

Finite Boundary: Exponential Tail

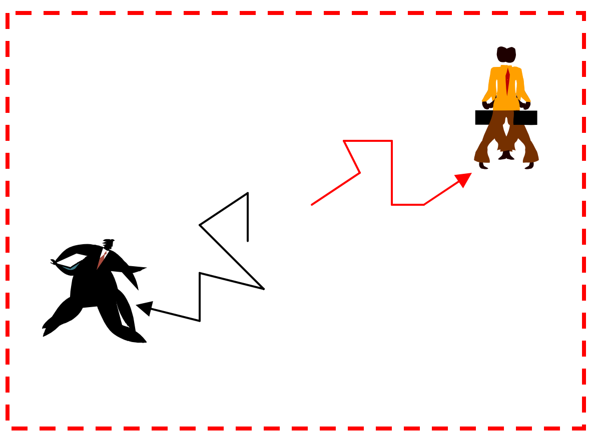


- Two nodes not meet for a long time

  → most likely move towards different directions

  → prolonged inter-meeting time

  <**strong memory**>



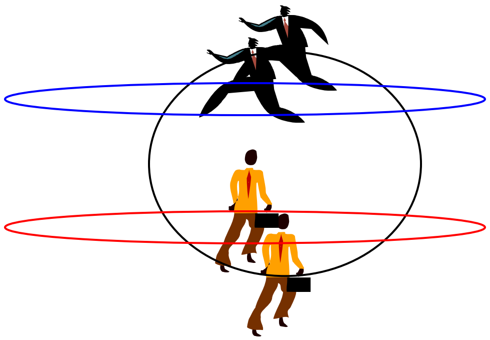
- Finite boundary erase this memory <**memoryless**>

  → resetting the memory in mobile trajectory

Other factors than the boundary?

- For most current synthetic models, finite boundary critically affects the “tail” behavior of inter-meeting time

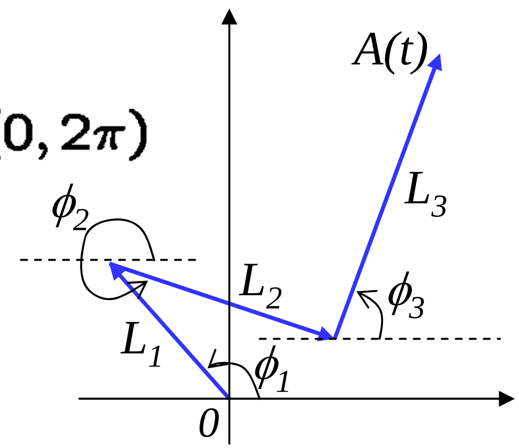
- Other possible factors
  - Dependency between mobile nodes
  - Heavy-tailed pause time (with infinite mean)
  - Correlation in the trajectory of mobile nodes



- Our study focuses on:
  - Independence or weak-dependence case
  - Efficient generation of realistic mobility trajectories for simulation with matching statistical properties

Removing the boundary …

- Discrete isotropic random walk in R^2
  - Choose a random direction uniformly from $[0, 2\pi)$
  - Travel for a random length L $\in$ $(0, \infty)$
  - Repeat the above process



Theorem 3: Two independent nodes A, B move according to the 2-D isotropic random walk model described above. Then, there exists constant $C > 0$ such that the inter-meeting time T_I satisfies

$$\boxed{P\{T_I > t\} \geq Ct^{-1/2},}$$ for all sufficiently large *t*.

Content

- Introduction
- **Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time**
  - Inter-meeting time with exponential tail
  - From exponential to power-law inter-meeting time
  - **Scaling the size of the space**
  - Simulation
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

Questions

About the boundary

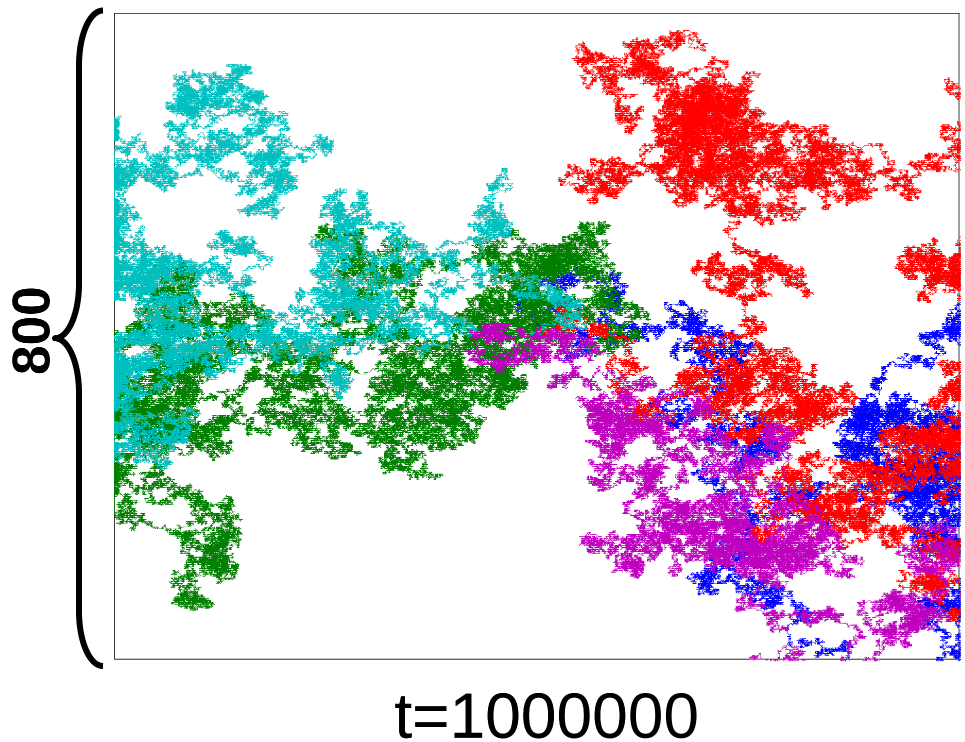
- In reality, all domain under study is bounded
- In what sense does "infinite domain" exist?

About exponential / power-law behavior

- "Where" does the transition from exponential to power-law take place?

Time / Space Scaling

- The **interaction** between the **timescale** under discussion and the **size** of the boundary
  - Standard BM: position scale as $O(\sqrt{t})$

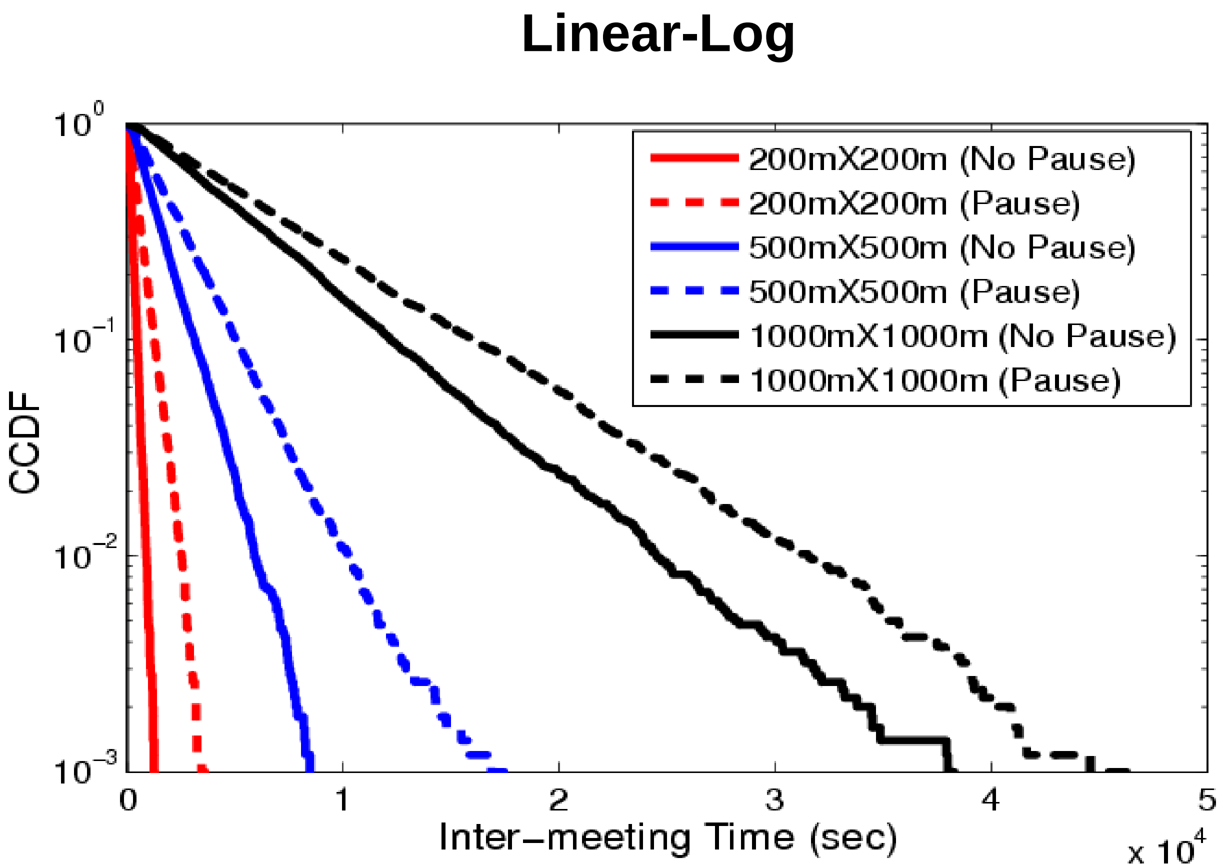


- Is 200X200 domain bounded?
  - Unbounded over time scale [0,100]
  - Bounded over time scale [0,1000000]
- KEY: whether the boundary effectively “erases” the memory of node’s movement

Content

- Introduction
- **Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time**
  - Inter-meeting time with exponential tail
  - From exponential to power-law inter-meeting time
  - Scaling the size of the space
  - **Simulation**
- Stochastic anatomy of the inter-meeting time under general mobility models
- Performance implications and outlook

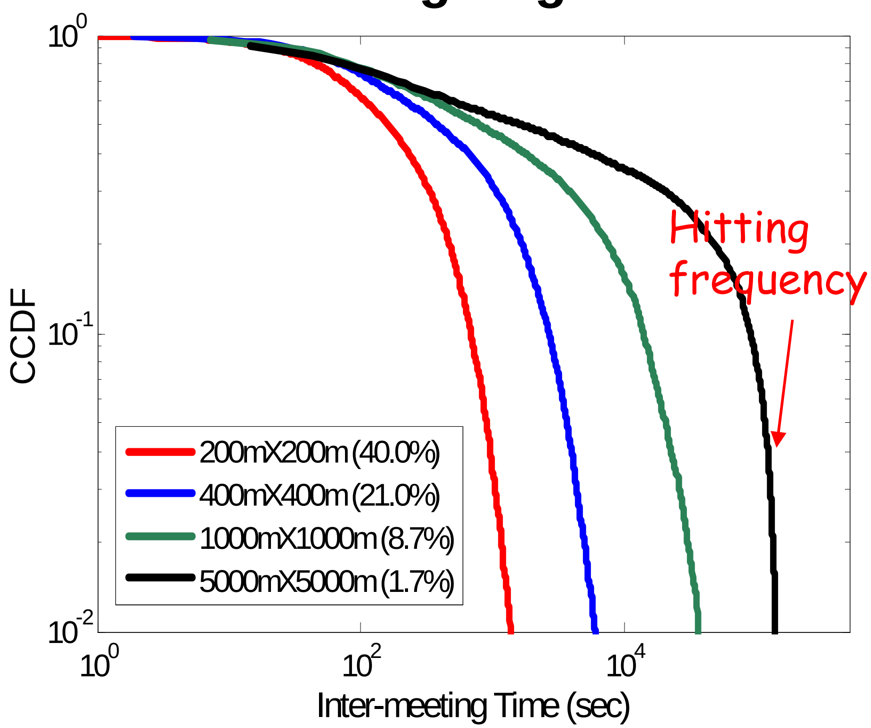
RWP



- Under given (fixed) domain: exponential behavior
  - Inherited memoryless property: resetting after two legs

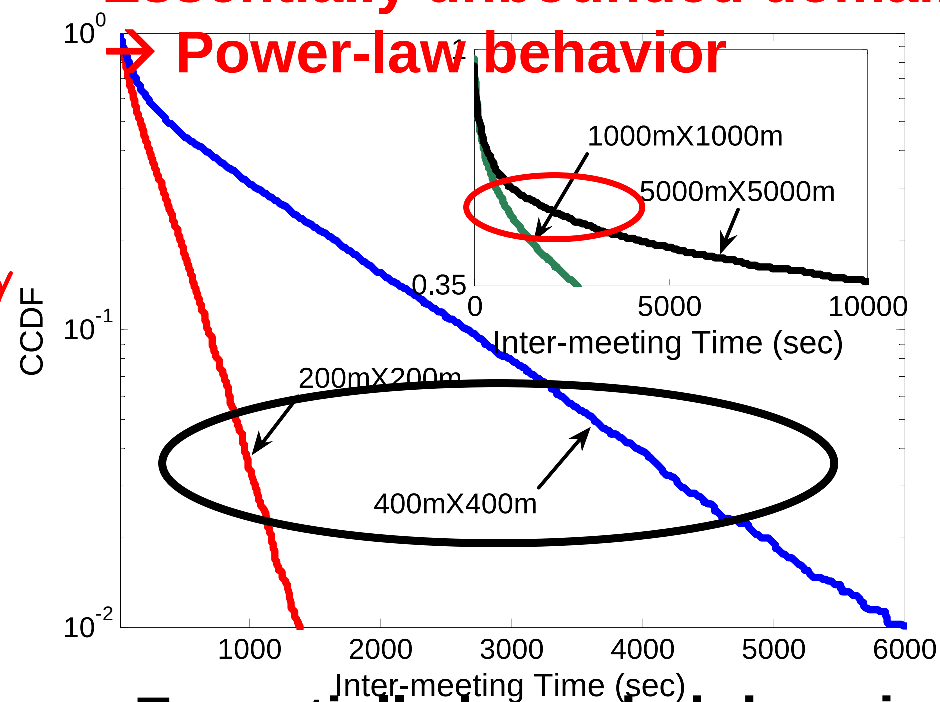
RWM

Log-Log



Linear-Log

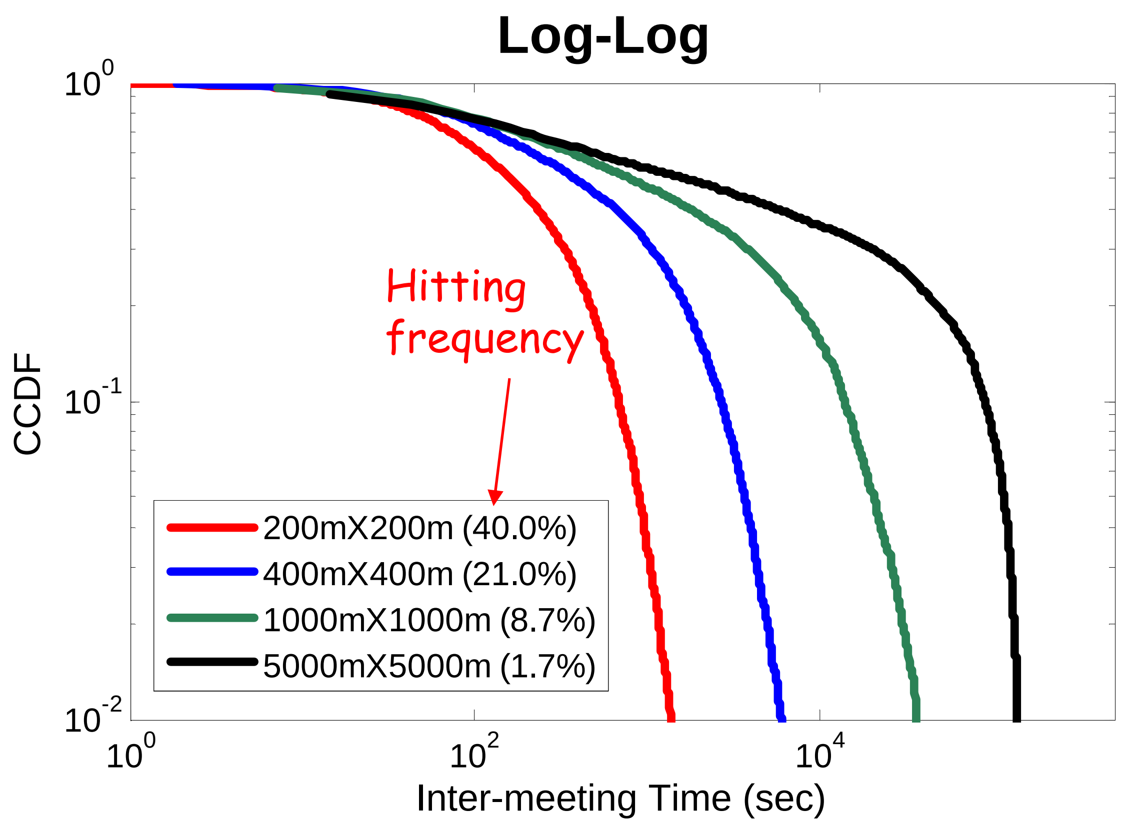
Essentially unbounded domain → Power-law behavior



Essentially bounded domain → Exponential behavior

- RWM: change direction uniformly every 50 seconds
- Speed: U(1.00, 1.68)
- Simulation period T: 40 hours

RWM



- RWM: change direction uniformly every 50 seconds
- Speed: U(1.00, 1.68)
- Simulation period T: 40 hours

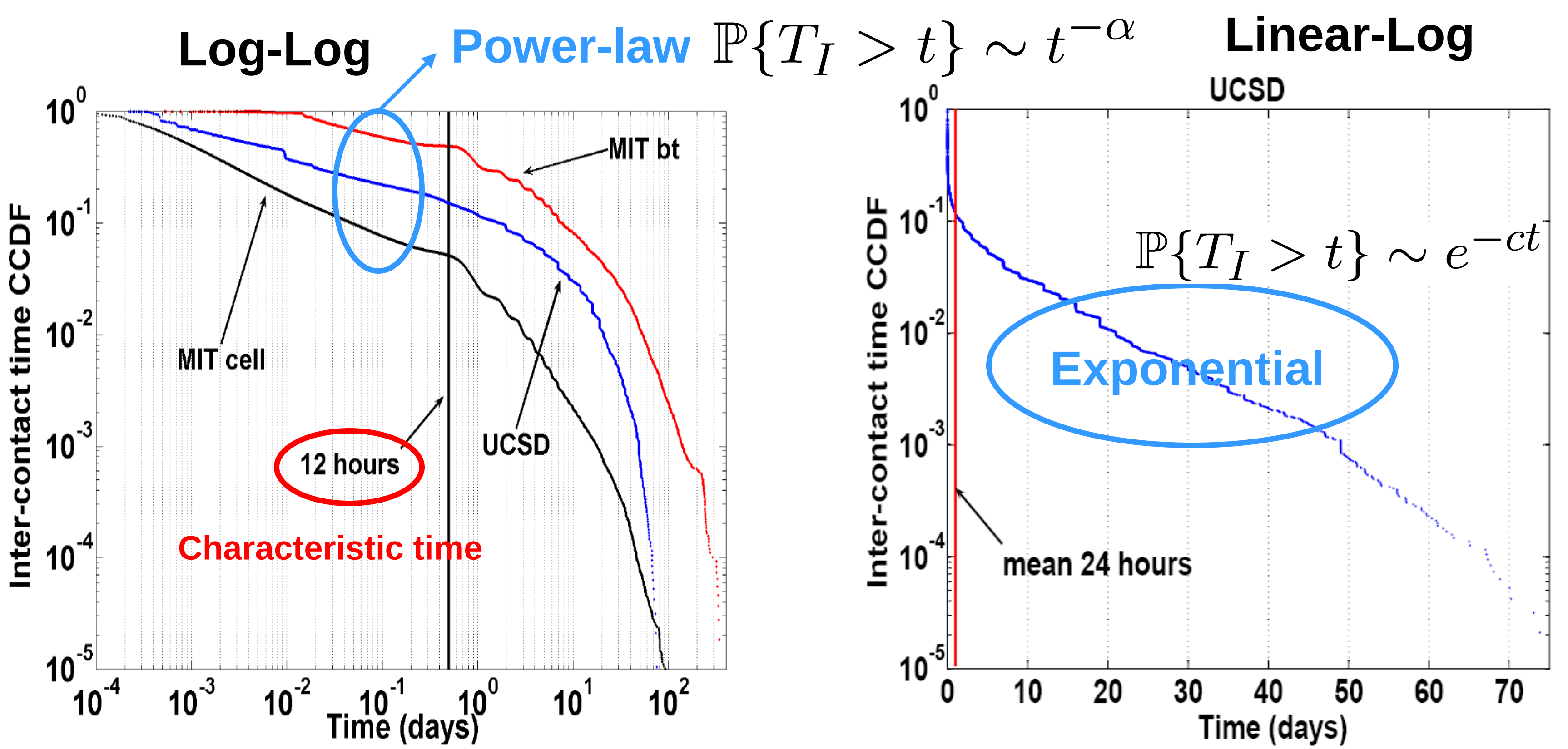
Summary of Part I

- "Finite boundary" is a decisive factor for the tail behavior of inter-meeting time; we formally prove
  - The exponential tailed inter-meeting time based on RWP, RWM model
  - The power-law tailed inter-meeting time after removing the boundary
- Time/space scaling, i.e., the interaction between domain size and time scale under discussion is the key to understand the effect of boundary

Content

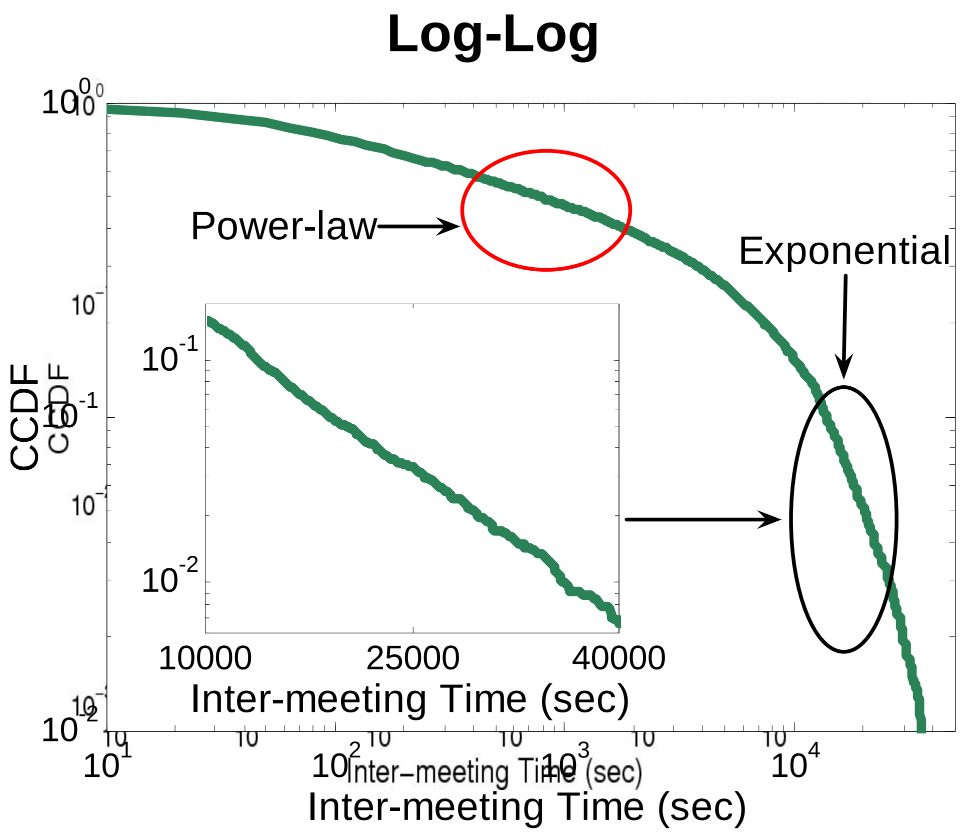
- Introduction
- Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time
- **Stochastic anatomy of the inter-meeting time under general mobility models**
  - **Head/Tail of Inter-meeting Time: A Closer Look at Dichotomy**
  - Stochastic Ordering for the Head of Inter-meeting Time
  - Invariance Property of Contact-based Metrics
- Performance implications and outlook

Mixture Behavior of Inter-meeting (1)



- T. Karagiannis, J.-Y. Le Boudec, and M. Vojnovic, "Power law and exponential decay of inter contact times between mobile devices," in *ACM MobiCom*, Montreal, Canada, Sept. 2007

Mixture Behavior of Inter-meeting (2)



- Model: 2-D isotropic RW
- Domain: 1000m x 1000m
- Time scale vs. Domain size
  - Within 1000 seconds, essentially unbounded domain → power-law
  - After 10000 seconds, essentially bounded domain → exponential
- Physical/virtual boundary

- Han Cai and Do Young Eun, "Crossing Over the Bounded Domain: From Exponential to Power-law Inter-meeting Time in MANET," in *ACM MobiCom*, Montreal, Canada, Sept. 2007 **(Best Student Paper Award)**

Mobility Model, Inter-meeting Time, and System Performance

- Case 1: Exponential [1]
  - Average (or “rate”) is enough
- Case 2: Power-law [2]
  - Heavy power-law inter-meeting → Infinite average delay
- Case 3: Hyper-exponential [3]
  - Too complicated to provide intuitive guideline for design
  - No consideration on mobility models

- [1] Grossglauser, M., and Tse, D. N. C. “Mobility increases the capacity of Ad Hoc wireless networks,” in *IEEE/ACM Transactions on Networking*, 2002.
- [2] 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 *IEEE INFOCOM*, 2006.
- [3] A. Al-Hanbali, A. A. Kherani, and P. Nain, “Simple models for the performance evaluation of a class of two-hop relay protocols,” in *IFIP Networking* 2007.

Mobility Model, Inter-meeting Time, and System Performance

General Mobility Models

↓

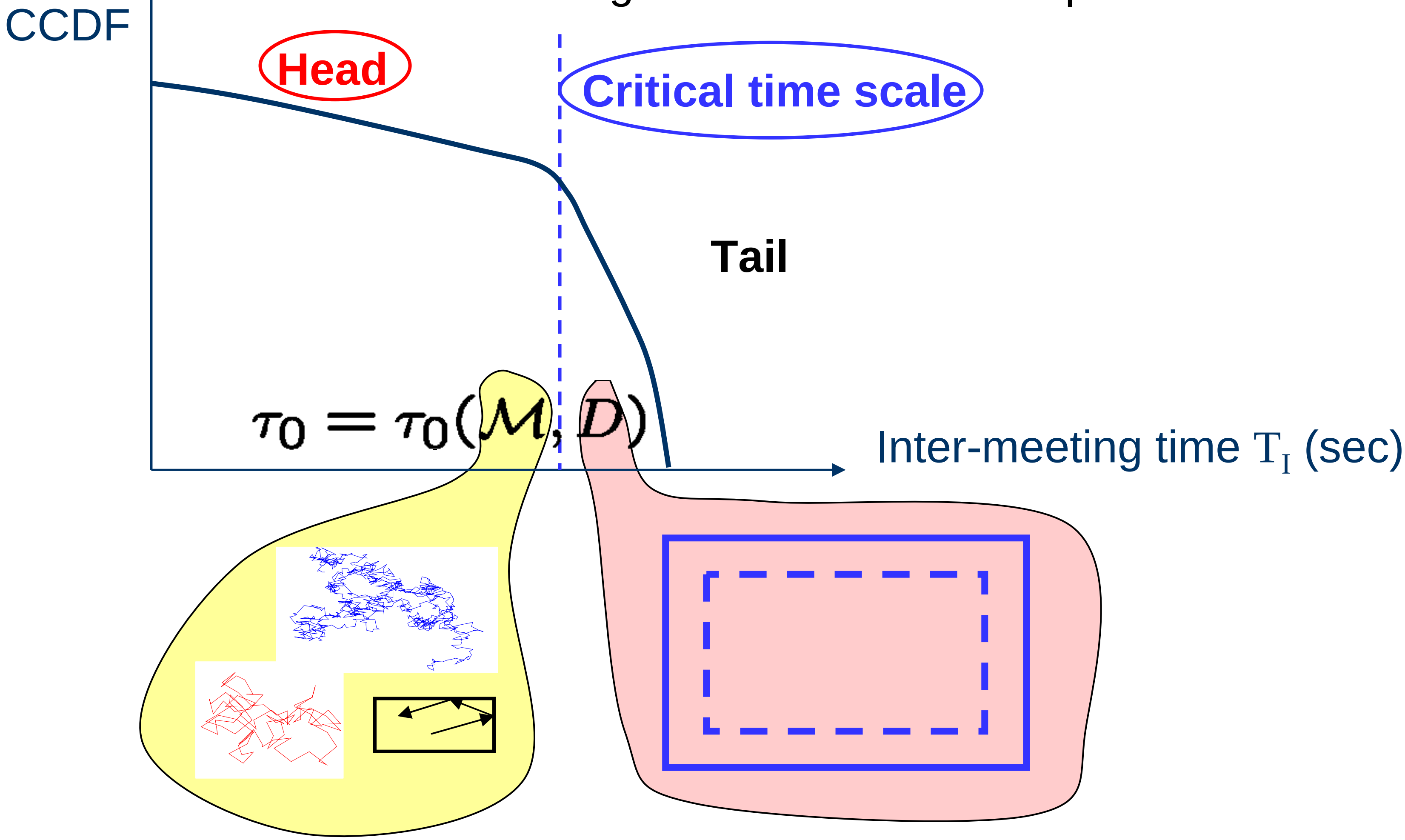
Inter-meeting Time Distribution with Mixture Behavior

↓

System Performance: capacity, delay, etc.

Stochastic Anatomy: Overview

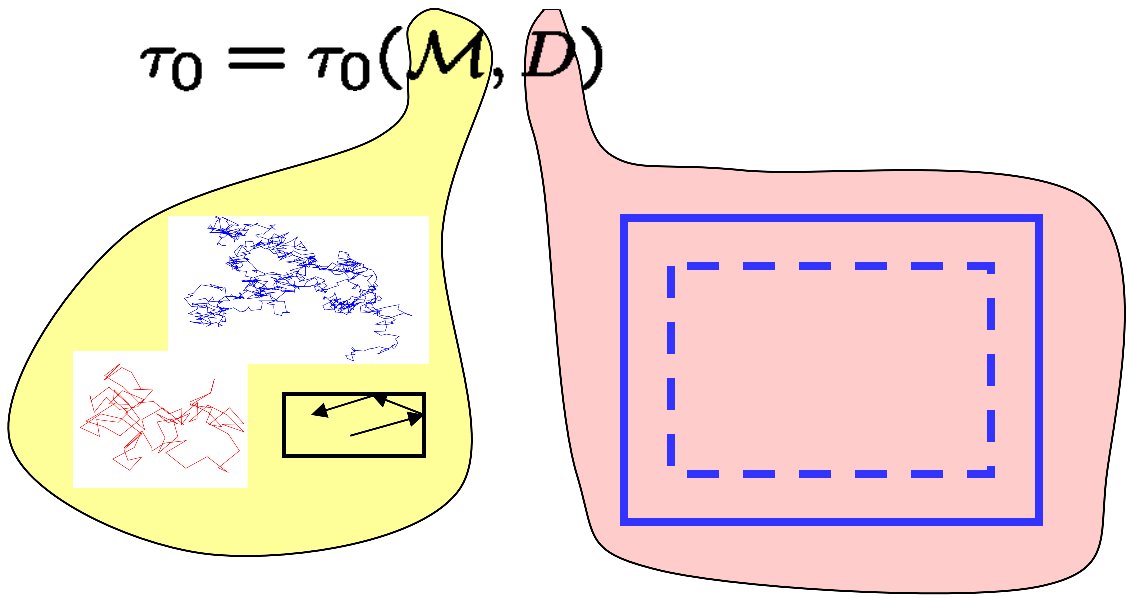
Effect of mobility model and domain size on
inter-meeting time distribution and performance



Regenerative Period (Critical Time Scale)

- Regenerative period: Timescale beyond which the inter-meeting time becomes of exponential type (tail)

$$\tau_0 = \tau_0(\mathcal{M}, D)$$



- [1] T. Karagiannis, J.-Y. Le Boudec, and M. Vojnovic, “Power law and exponential decay of inter contact times between mobile devices,” in *ACM MobiCom*, Montreal, Canada, Sept. 2007
- [2] Han Cai and Do Young Eun, “Crossing Over the Bounded Domain: From Exponential to Power-law Inter-meeting Time in MANET,” in *ACM MobiCom*, Montreal, Canada, Sept. 2007

Regenerative Period (Critical Time Scale)

- Regenerative period: Timescale beyond which the inter-meeting time becomes of exponential type (tail)

$$\tau_0 = \tau_0(\mathcal{M}, D)$$

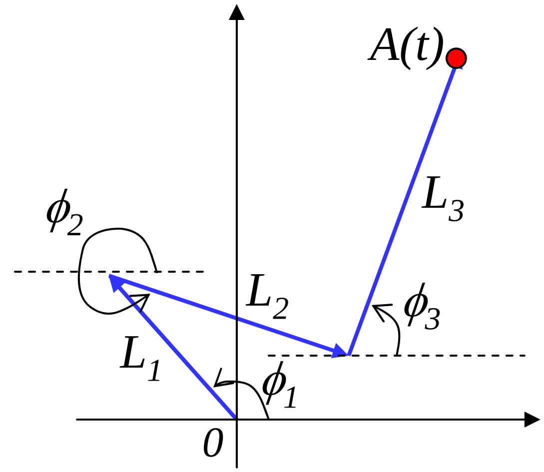
- Similar to the characteristic time [1]
- Interaction between domain size and time scale [2]
  - Same order of the typical amount of time it takes for the node to travel *D* distance
  - Head ($t \ll \tau$): power-law; Tail ($t \gg \tau$): exponential

- [1] T. Karagiannis, J.-Y. Le Boudec, and M. Vojnovic, “Power law and exponential decay of inter contact times between mobile devices,” in *ACM MobiCom*, Montreal, Canada, Sept. 2007
- [2] Han Cai and Do Young Eun, “Crossing Over the Bounded Domain: From Exponential to Power-law Inter-meeting Time in MANET,” in *ACM MobiCom*, Montreal, Canada, Sept. 2007

Effect of Boundary $\tau_0 = \tau_0(\mathcal{M}, D)$

- Average displacement

$$\sigma(t) = \sqrt{\mathbb{E}\{|A(t)|^2\}}$$



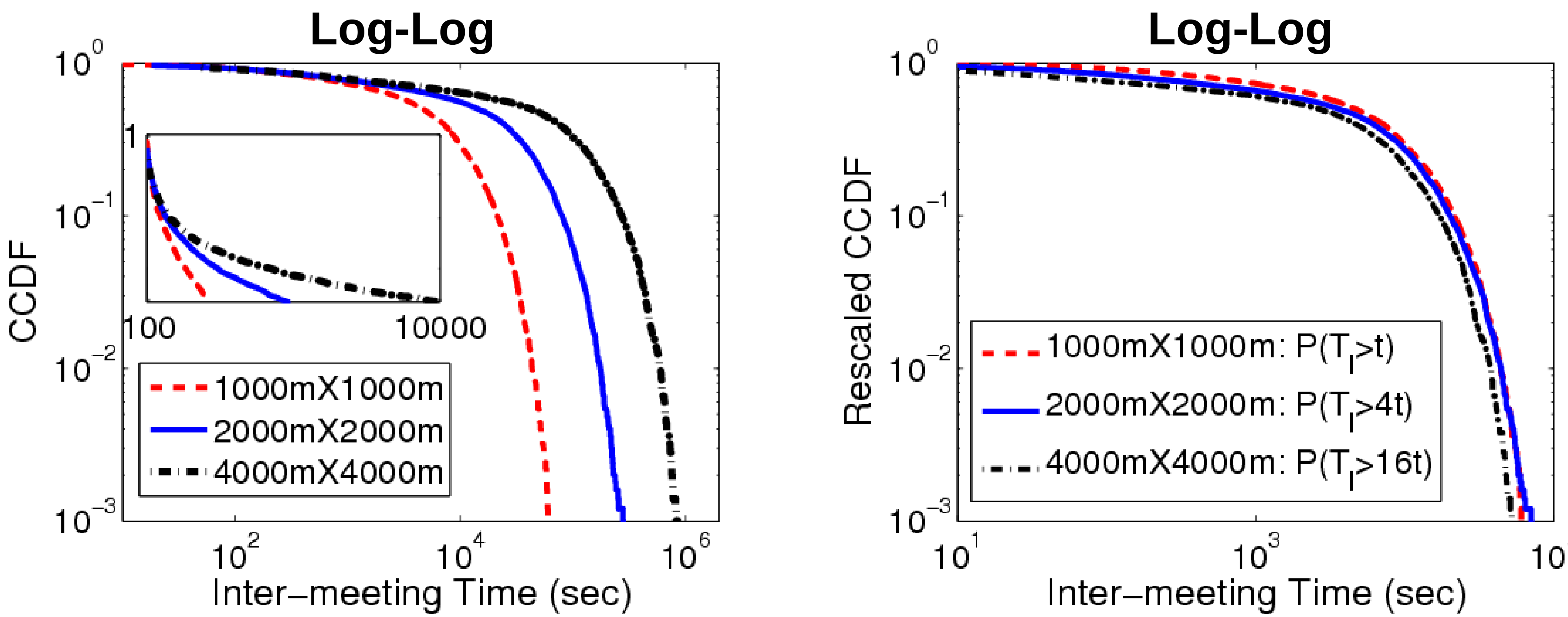
- For IRW: $\sigma(t) \sim \sqrt{t}$

- Relationship between τ_0 and D:

$$\sigma(\tau_0) = D \qquad \tau_0 \propto D^2$$

- Quantitatively observe this scaling behavior $\mathbb{P}\{T_I > \eta t\}, \quad (\eta \propto D^2)$

Effect of Boundary $\tau_0 = \tau_0(\mathcal{M}, D)$ (2)

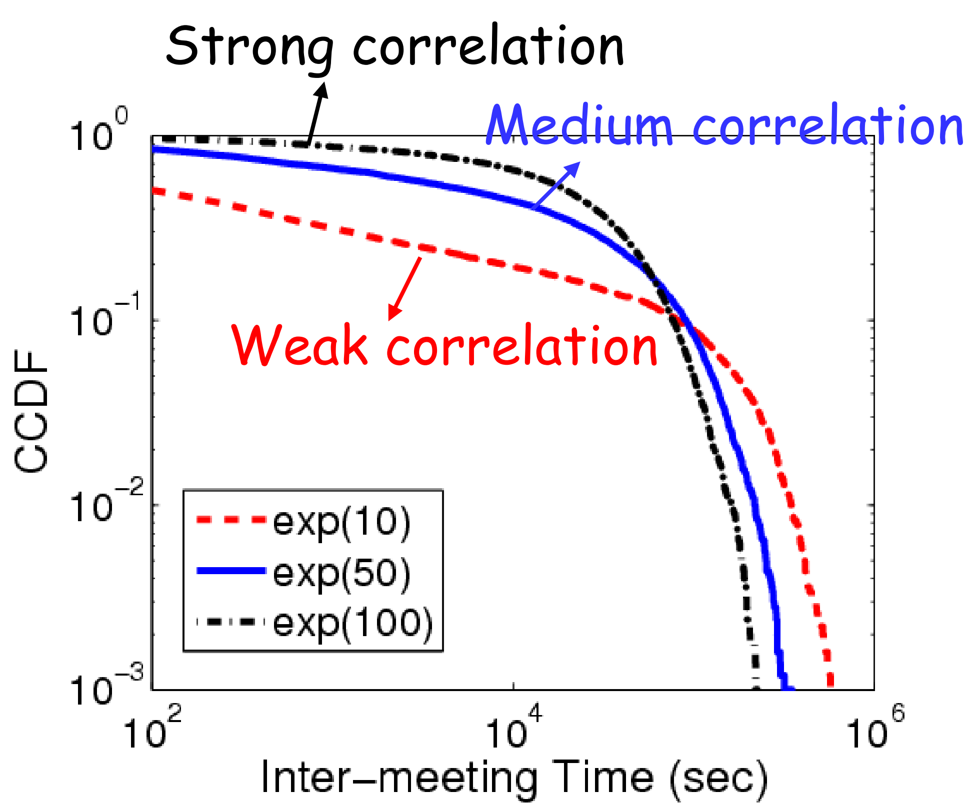


$\mathbb{P}\{T_I > t\}$ $\mathbb{P}\{T_I > \eta t\}, \quad (\eta \propto D^2)$

- Effect of domain size on τ_0
  - Step length: exp(100)

Effect of Mobility Models: $\tau_0 = \tau_0(\mathcal{M}, D)$

Log-Log

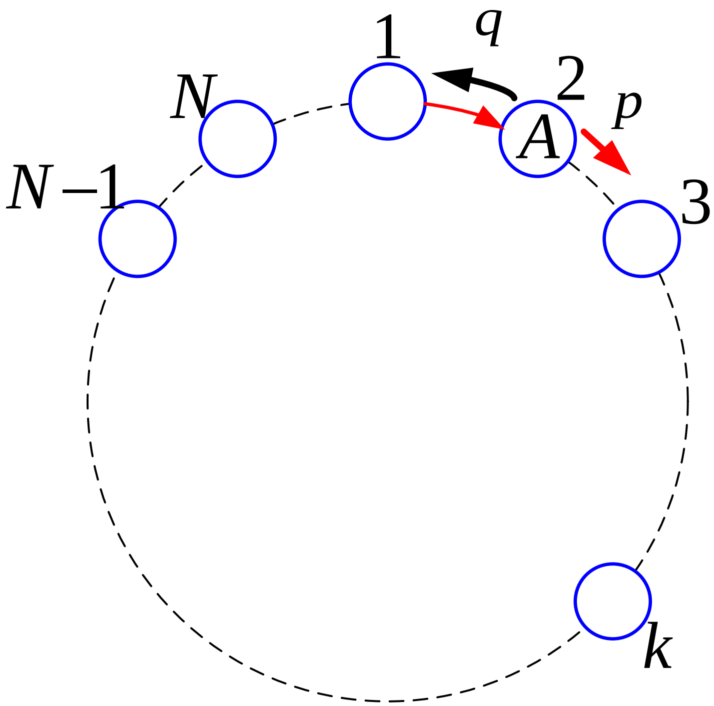


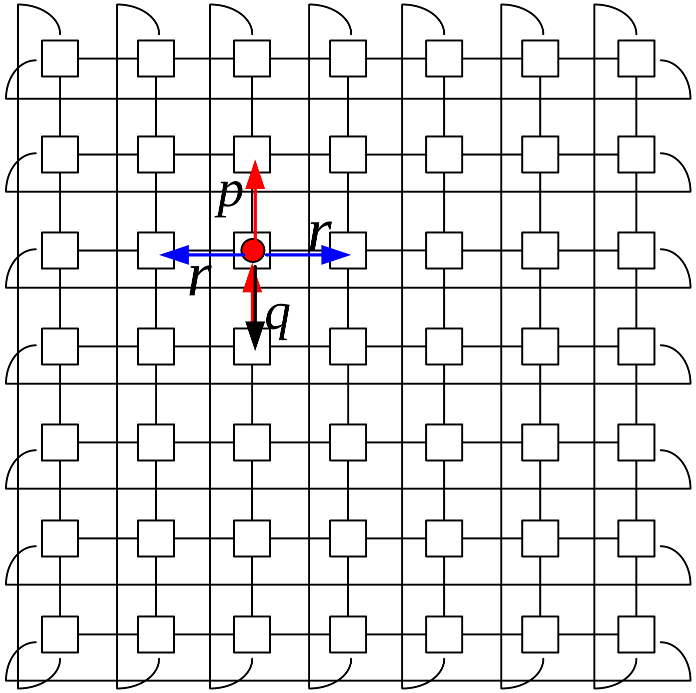
- Effect of `correlation' of mobility models on τ_0
  - Step length: exp(10), exp(50), exp(100).
    - Large average step length → stronger correlation
  - Domain: 2000m x 2000m
  - Stronger correlation in mobility pattern leads to smaller τ_0

Content

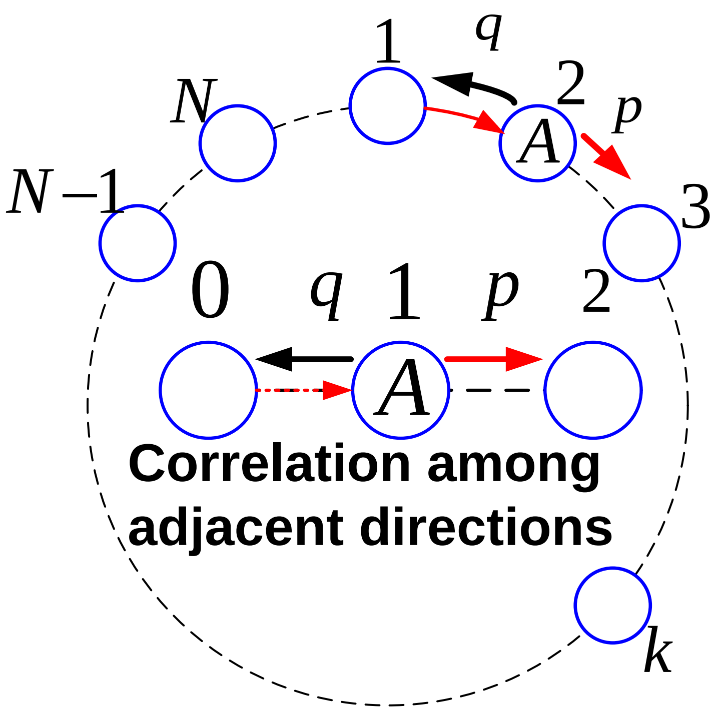
- Introduction
- Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time
- **Stochastic anatomy of the inter-meeting time under general mobility models**
  - Head/Tail of Inter-meeting Time: A Closer Look at Dichotomy
  - **Stochastic Ordering for the “Head” of Inter-meeting Time**
  - Invariance Property of Contact-based Metrics
- Performance implications and outlook

Correlated Random Walk (CRW)





Correlated Random Walk (CRW)



$$p = \mathbb{P}\{\text{follow same direction}\}$$

$$q = \mathbb{P}\{\text{follow opposite direction}\}$$

$$p + q = 1$$

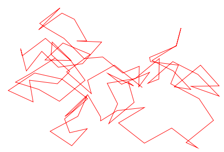
$$\rho = p - q$$

- Simple RW: $\rho = 0$; Bouncing: $\rho = -1$; Straight-line: $\rho = 1$
- \`Head' of inter-meeting time:
  - Reside in an essentially unbounded domain: we let $N \to \infty$

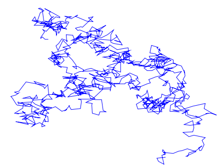
Stochastic Ordering for T_I

- **Theorem 4:** Let T_I be the inter-hitting time of a mobile node C to the origin in an unbounded 1-D grid. Then, for any given $t > 0$, $P\{T_I > t\}$ is an increasing function of $\rho \in [0, 1)$.

Correlation coefficient



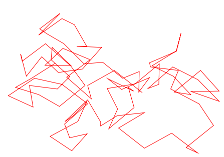
$$\boxed{\rho_1 \geq \rho_2}$$



$$\boxed{\mathbb{P}\{T_I^{(\rho_1)} > t\} \geq \mathbb{P}\{T_I^{(\rho_2)} > t\}}$$

Mobility pattern with ρ_1 has stronger correlation

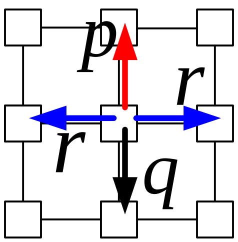
$$T_I^{\rho_1} \geq_{st} T_I^{\rho_2}$$

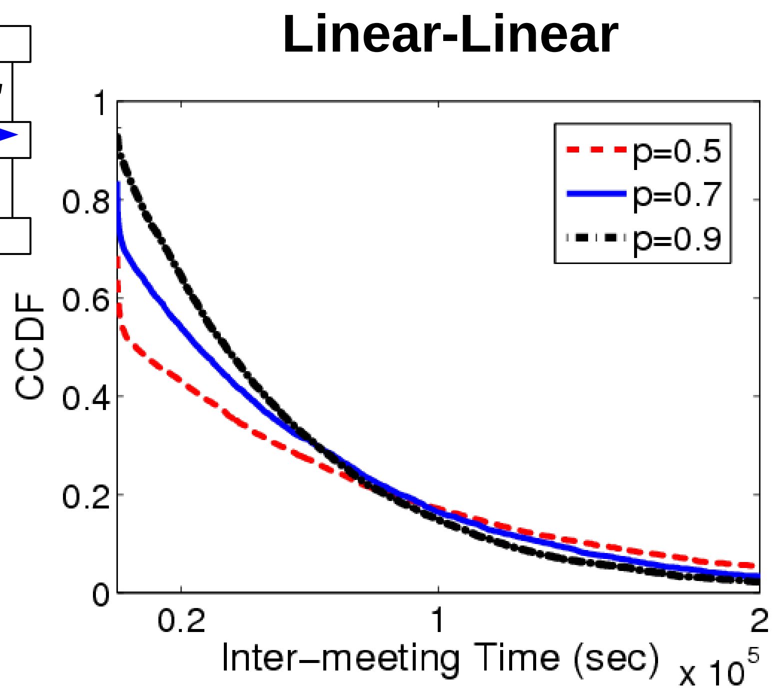


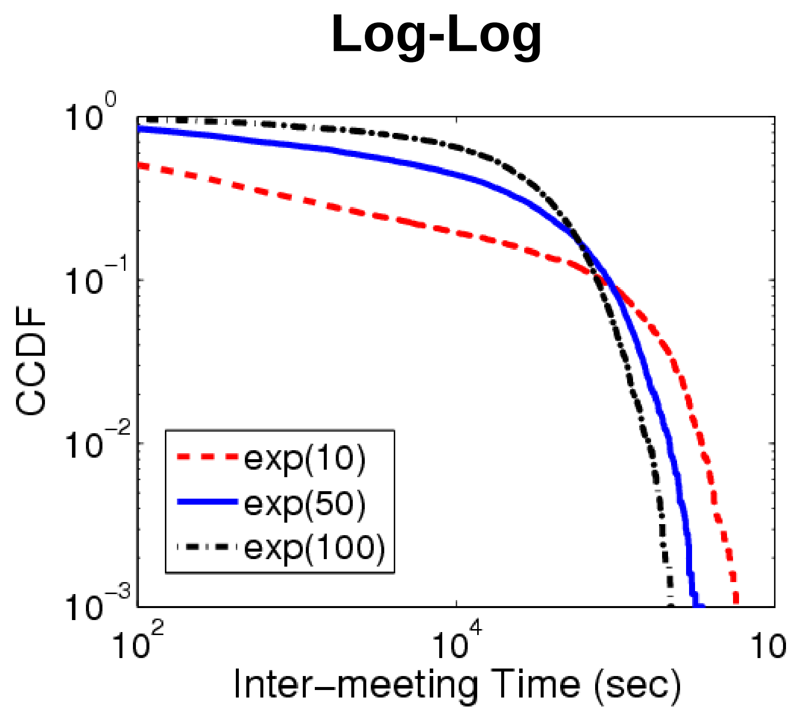
stronger correlation → **heavier head** in the CCDF of the inter-meeting time

Extensions to 2-D CRW

$$q = r = (1 - p)/3$$





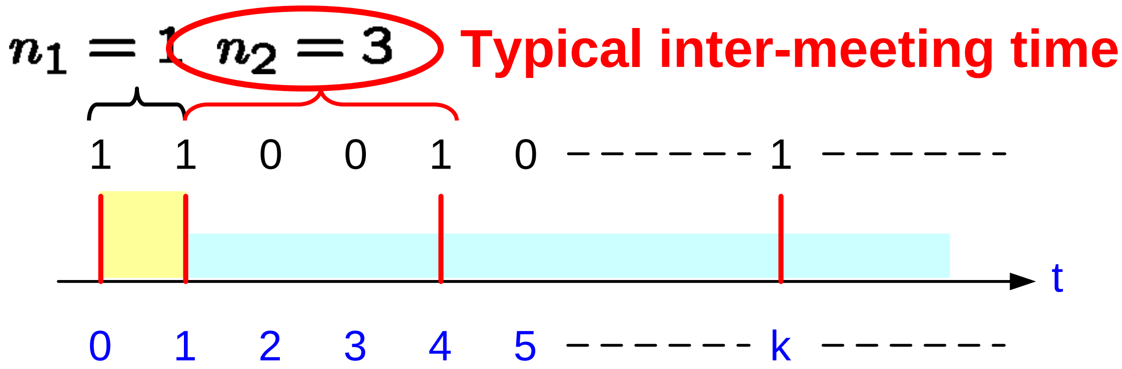


- 2-D CRW (200 x 200 grid)
  - Correlation: simple RW (zero) → nearly go straight line (strong)
  - Head of inter-meeting: light → heavy

Content

- Introduction
- Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time
- **Stochastic anatomy of the inter-meeting time under general mobility models**
  - Head/Tail of Inter-meeting Time: A Closer Look at Dichotomy
  - Stochastic Ordering for the “Head” of Inter-meeting Time
  - **Invariance Property of Contact-based Metrics**
- Performance implications and outlook

Contact Indicator Process



- Contact Indicator process: $Y_t = \begin{cases} 0 & \text{out of contact} \\ 1 & \text{in contact} \end{cases}$
- Recurrence time $\{n_l\}_{l \geq 1}$ of state 1

$$T_1 \triangleq \min\{t \geq 0 : Y_t = 1\},\ T_k \triangleq \min\{t > T_{k-1} : Y_t = 1\}\ (k \geq 2),$$
$$n_l \triangleq T_{l+1} - T_l.$$

Kac's Theorem for Ergodic Seq.

- **Kac's Theorems:** For a stationary $0-1$ process $\{Y_t\}$ $(t = 0, 1, 2, \ldots)$ with 'eventually-occurring' state 1: **Expected time between two adjacent recurrences**

$$\mathbb{E}\{n_1 | Y_0 = 1\} = 1/\mathbb{P}\{Y = 1\}, \tag{1}$$

$$\mathbb{E}\{n_1 | Y_0 = 1,\ Y_1 = 0\} = 1 + \frac{1 - \mathbb{P}\{Y = 1\}}{\mathbb{P}\{Y = 1\} - \mathbb{P}\{Y_0 = 1, Y_1 = 1\}}. \tag{2}$$

Expected time between two adjacent recurrences given Y_t first gets out of state 1

- Average recurrence time depends only on marginal distribution
  - Ergodic Markov Chain: well-known
  - General contact indicator process: stationary, but not MC !!
- Inter-meeting time: recurrence time getting out of "state 1" first
  - Short contact: (1) and (2) reduce to the same formula
- V. Balakrishnan, G. Nicolis, and C. Nicolis, "Recurrence time statistics in deterministic and stochastic dynamical systems in continuous time: a comparison," *Phys. Rev. E*, 61(3):2490–2499, Mar 2000.

Invariance Property of Contact Metrics

Theorem 5: The averages of T_H, T_I and T_C of CRW <u>do not</u> depend on $\rho \in (-1, 1)$. Specifically,

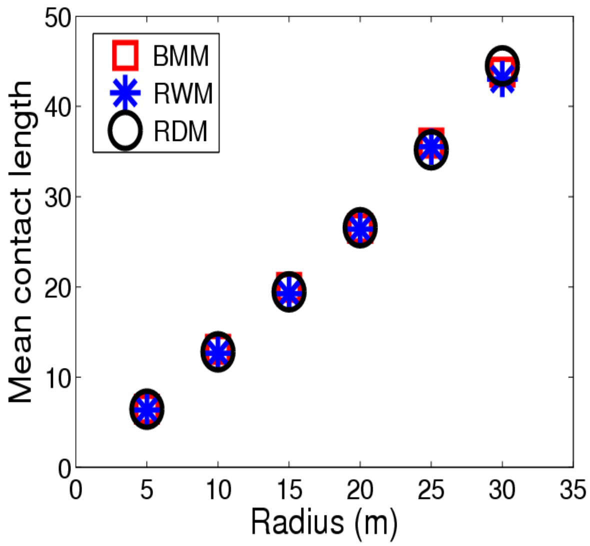
$$\mathbb{E}\{T_H\} = N-1, \ \mathbb{E}\{T_I\} = 2(N-1), \ \mathbb{E}\{T_C\} = 2.$$

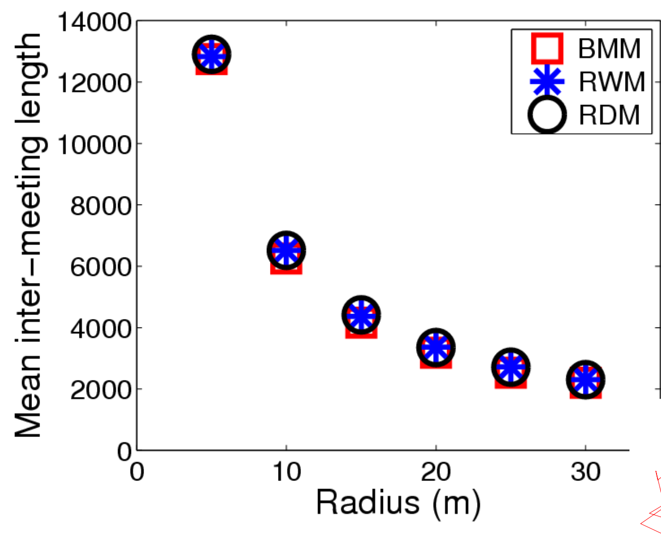
Inter-hitting **Inter-meeting** **Contact**

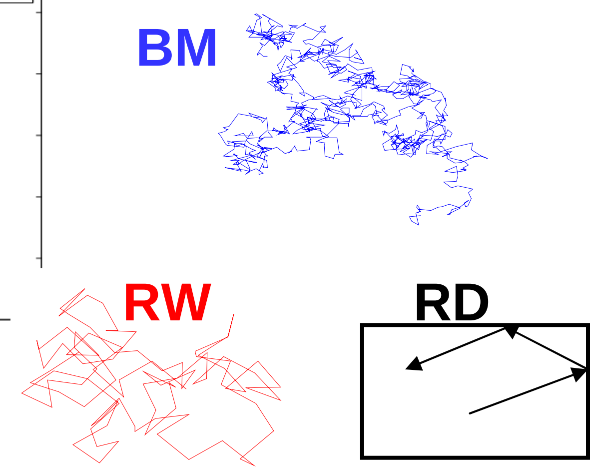
- Average contact-based metrics using 1-D simple RW model [1]
- We greatly extend the results in [1] into:
  - 2-D <u>Correlated</u> RW (CRW) model
  - General inter-contact to a set of nodes
  - Under both Boolean and SINR interference models

- [1] T. Karagiannis, J.-Y. Le Boudec, and M. Vojnovic, "Power law and exponential decay of inter contact times between mobile devices," in *ACM MobiCom*, Montreal, Canada, Sept. 2007

Invariance Property of IRW Models



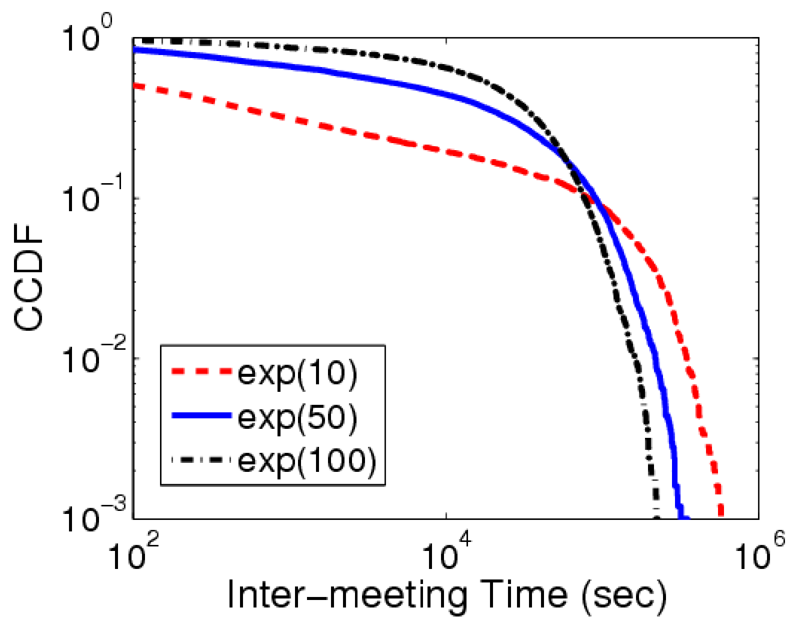




- Mean contact/inter-meeting time: invariant w.r.t. mobility model (step-length dist.)
  - Mobility model: BM (const: 8), RW (exp: 40), RD
  - Boolean interference model: 400m x 400m, v = 1m/s

Convex Ordering of Inter-meeting Time

- Stronger correlation
  - Heavier `head' of inter-meeting distribution
  - Same average
  - **Lighter `tail' to offset**
  - Suggest a **convex ordering** relationship



$$T_{I1} \leq_{cx} T_{I2}, \text{ i.e., } \mathbb{E}\{\phi(T_{I1})\} \leq \mathbb{E}\{\phi(T_{I2})\} \ (\forall \text{ convex } \phi(\cdot))$$

In particular, $\mathbb{E}\{T_{I1}\} = \mathbb{E}\{T_{I2}\}$ and $\mathbb{E}\{T_{I1}^2\} \leq \mathbb{E}\{T_{I2}^2\}$

- A. Muller and D. Stoyan, "Comparison Methods for Stochastic Models and Risks" John Wiley & Son, 2002

Content

- Introduction
- Crossing Over the Bounded Domain: from exponential to power-law inter-meeting time
- Stochastic anatomy of the inter-meeting time under general mobility models
    - Head/Tail of Inter-meeting Time: A Closer Look at Dichotomy
    - Stochastic Ordering for the "Head" of Inter-meeting Time
    - Invariance Property of Contact-based Metrics
- **Performance Implications and Outlook**

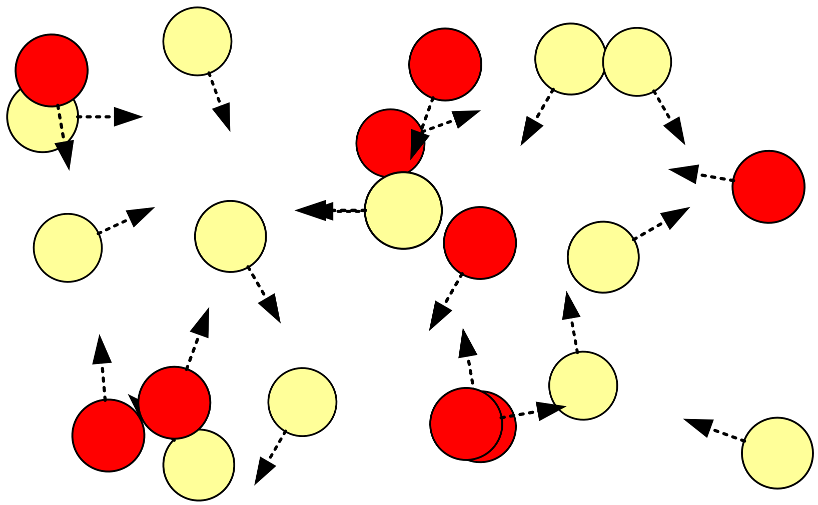
Mobility impacts performance…

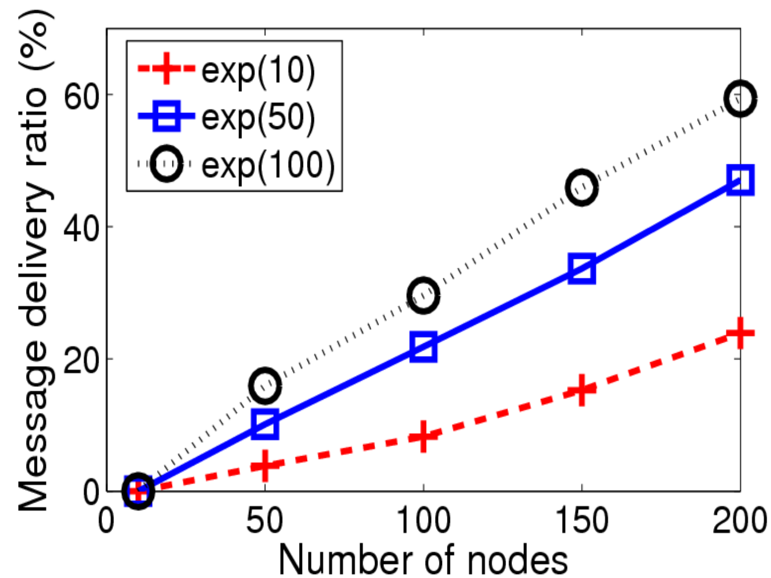
- **Well-known facts:**
  - Different mobility models lead to different performances…
  - Stationary distribution of mobile nodes under a given model
    - RWP, Random Walk (Brownian motion), Random Direction (RD), etc.
- **“Poisson contact” assumption entitles you to**
  - focus only on the “average” contact rate among mobile nodes
  - differentiate performance in terms of densities of nodes (contact rates)
  - proceed with Markovian analysis
- **Invariance property is here !**
  - “Average contact rate” does NOT depend on the step-length distributions of 2-D isotropic random walk (very general class)

Mobility impacts performance…

- **Still, not so well-known:**
  - **How** exactly does the mobility pattern impact the performance? In what sense?
  - Lacks systematic way to predict performances over a given mobility pattern
- **Myth of Poisson Contact fails:**
  - Inter-meeting (inter-contact) time among mobile node is far from being memoryless (instead, more of "dichotomic" type)
- How does the **entire distribution of T_I** affect performance of a given protocol?

Motivating Example

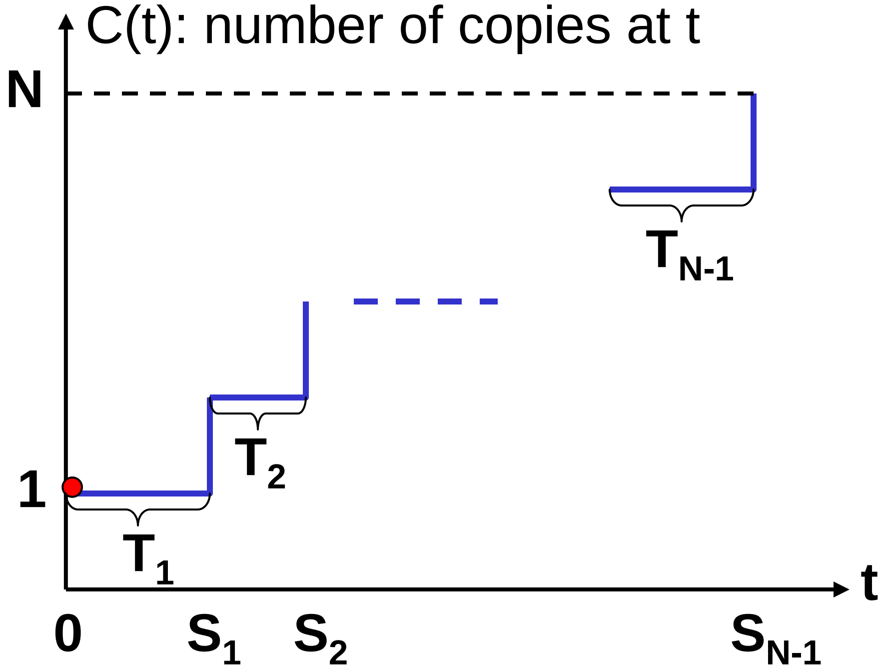


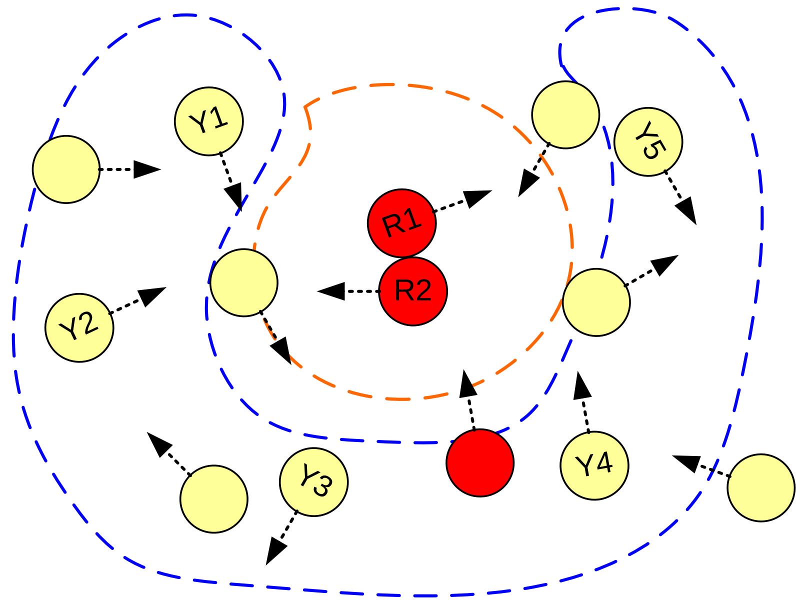


- Epidemic routing (ER) protocol
  - Similar to virus spreading

- Message delivery ratio under ER
- IRW with different step-length distributions
- **But they all have the same "average contact rates"!!**

Epidemic Forwarding/Routing and First Passage Time





Remaining inter-meeting time between

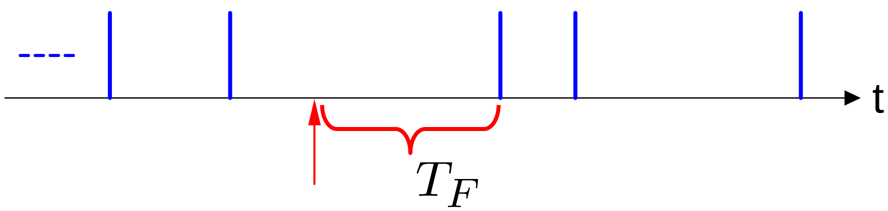
$$(R1, Y1),\ (R1, Y2),\ \cdots,\ (R1, Y5)$$
$$(R2, Y1),\ (R2, Y2),\ \cdots,\ (R2, Y5)$$

$$T_n = \inf\{t : C(t) = n+1\} - \inf\{t : C(t) = n\} = \min\{T^F_{n,1}, \ldots, T^F_{n,n(N-n)}\}$$

Random observation time instance→ the First Passage Time (FPT)

Ordering of FPT

- Relationship with the inter-meeting time



$$\mathbb{P}\{T_F > t\} = \frac{1}{\mathbb{E}\{T_I\}} \int_t^{\infty} \mathbb{P}\{T_I > s\} ds$$

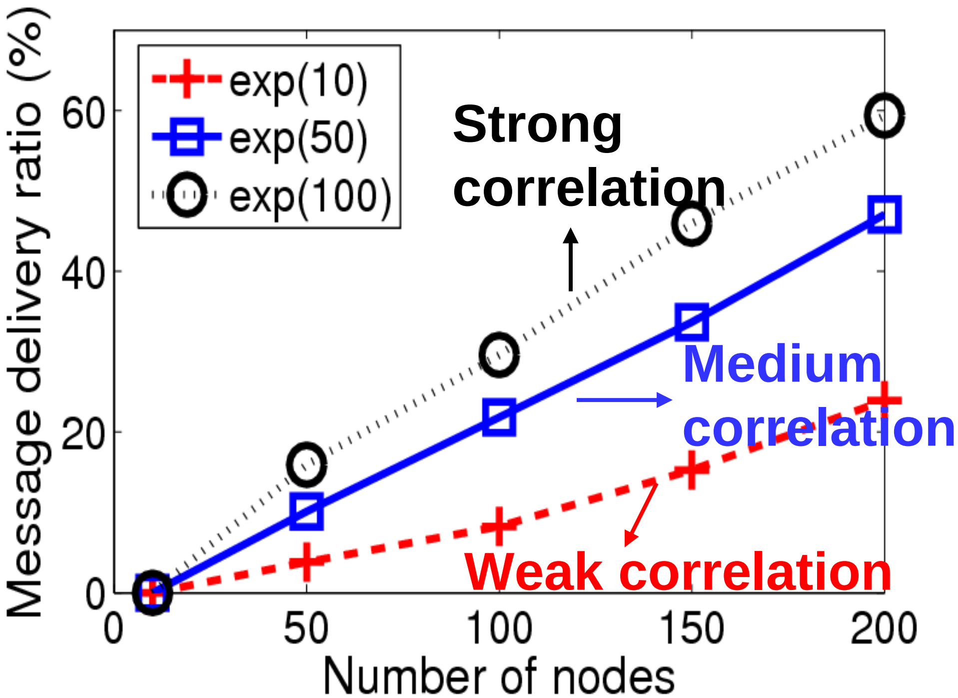
Equilibrium distribution

- Convex ordering of inter-meeting times: $T_{I1} \leq_{cx} T_{I2}$
- This implies stochastic ordering of FPTs

$$\mathbb{P}\{T_{F1} > t\} = \frac{\mathbb{E}\{[T_{I1} - t]^+\}}{\mathbb{E}\{T_{I1}\}} \leq \frac{\mathbb{E}\{[T_{I2} - t]^+\}}{\mathbb{E}\{T_{I2}\}} = \mathbb{P}\{T_{F2} > t\}$$

  - In particular, $\mathbb{E}\{T_{F1}\} \leq \mathbb{E}\{T_{F2}\}$

Ordering of Performance via T_I, T_F



- The same epidemic routing protocol
  - Domain: 2000 x 2000 m
  - Model: RW with exp(10), exp(50), exp(100)
  - 1800 packets generated at the beginning
  - Observe time instance: 6000 seconds

- Stronger correlation → stochastically smaller T_F → larger message delivery ratio

Summary & Outlook

- Our work is on stochastic analysis of mobility models, induced contact-based metrics, and ordering of network performance
  - Non-Poisson contact, “head” and “tail” of the inter-meeting time dist., time/space scaling with domain size
  - Convex ordering, invariance property for general mobility models with correlations
- Questions remain…
  - Other (more complicated) protocols over non-Poisson contacts?
  - Issues of delay, capacity (throughput), and cost (# of copies) under general mobility
  - Systematic design of better protocols/mobility toward high performance MANET in the face of non-Poisson contacts

Thank You!!

Questions & Answers