Scaling Properties of Delay Tolerant Networks with Correlated Motion Patterns

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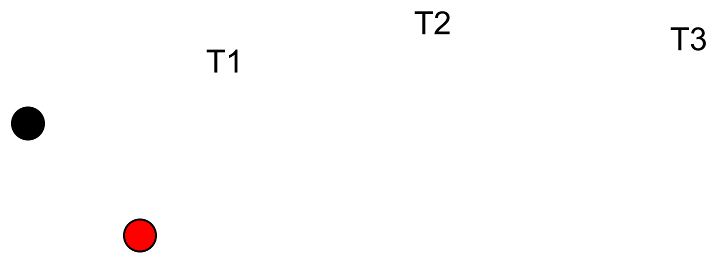
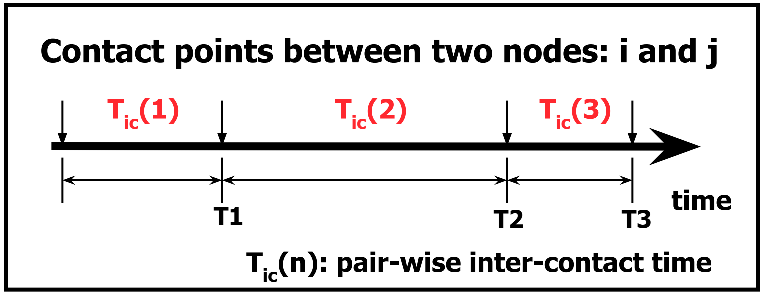
Key DTN Metric: Pair-wise Inter-contact Time

Key metric for measuring *end-to-end delay*

Pair-wise inter-contact time: interval between two contact points



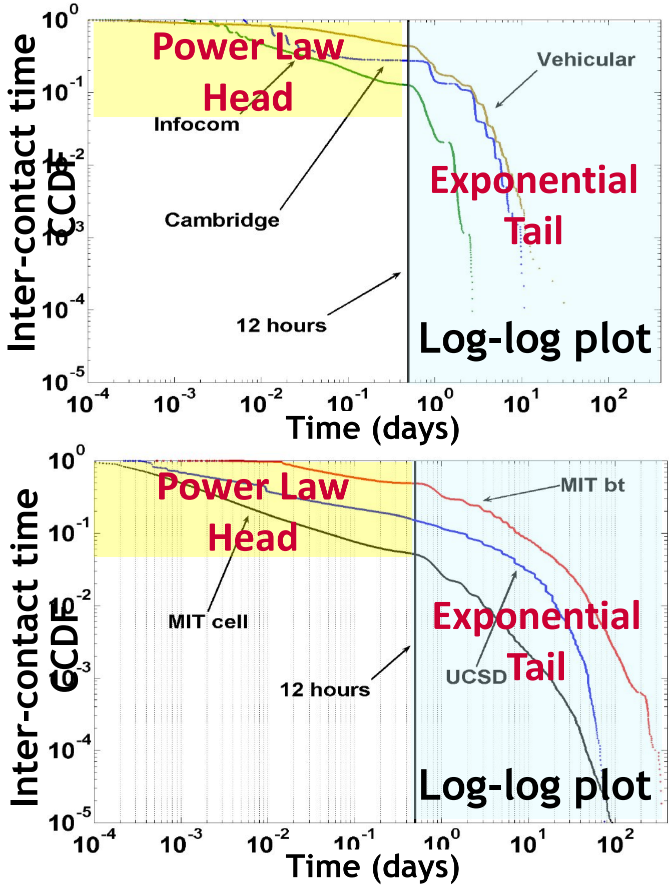


Inter-contact distribution:

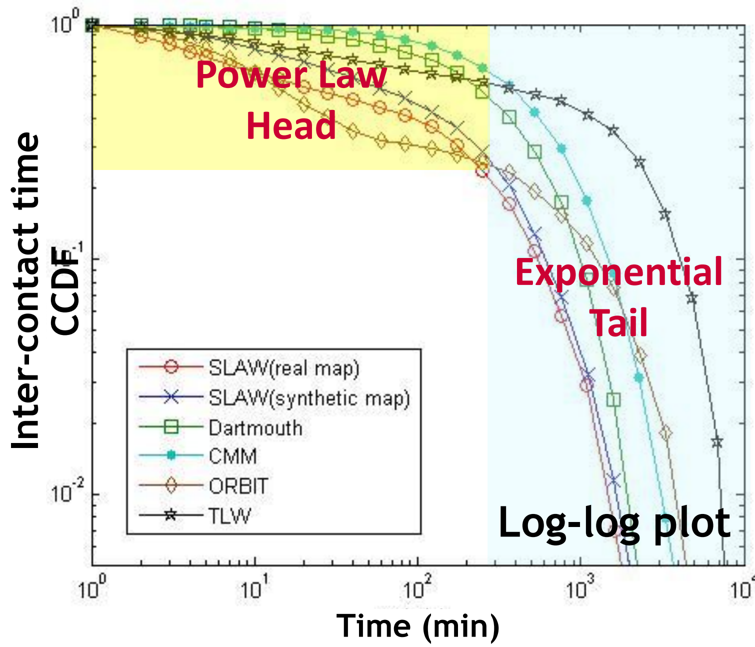
- Exponential ☺: bounded delay, but not realistic?
- Power-law ☹ : may cause infinite delay, but more realistic?

Two-phase Inter-contact Time

Two-phase distribution: power-law head and exponential tail



Karagiannis et al., MobiCom'07



Levy walk based mobility
Lee et al. Infocom'08/09

- Association times w/ AP (UCSD) or cell tower (MIT cell)
- Direct contact traces: Infocom, cambridge (imotes), MIT-bt

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Two-phase Inter-contact Time

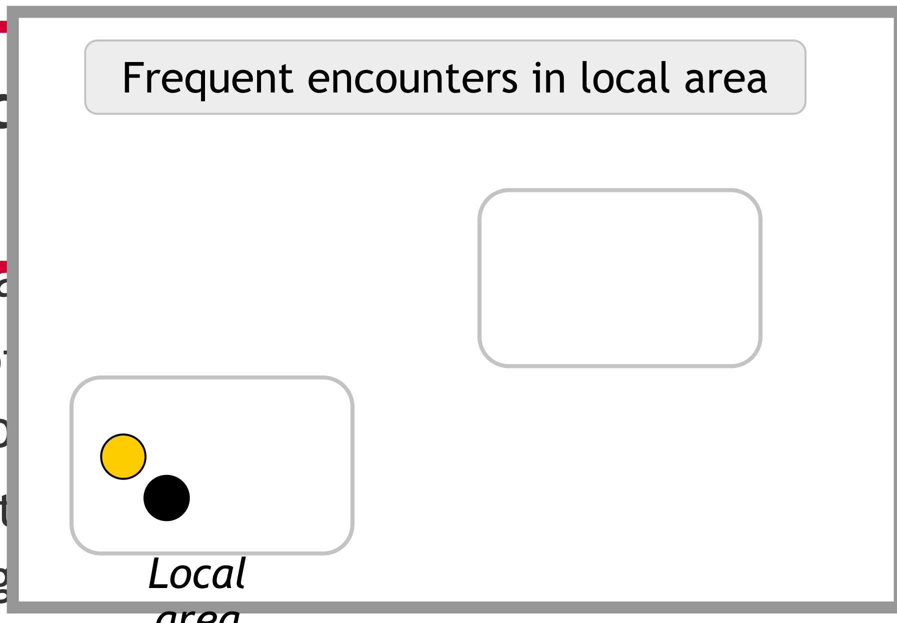
Why two-phase distribution? One possible cause:

- Flight distance of each random trip (within a finite area) [Cai08]
- The shorter the **flight distance**, the higher the **motion correlation** in local area, resulting heavier power-law head
  - Power-law head while in local area vs. exponential tail for future encounters

Goal: und… …ted motion patterns on… …ng properties

each other; a…

  - Levy flight o… …casional long flights
- Vehicular mo… …raffic jam)
  - High correlat…
  - After leaving… …night"



*Cai08: Han Cai and Do Young Eun, Toward Stochastic Anatomy of Inter-meeting Time Distribution under General Mobility Models, MobiHoc'08
*Rhee08: Injong Rhee, Minsu Shin, Seongik Hong, Kyunghan Lee and Song Chong, On the Levy-walk Nature of Human Mobility, INFOCOM'08

DTN Model: *Inter-contact rate + flight distance*

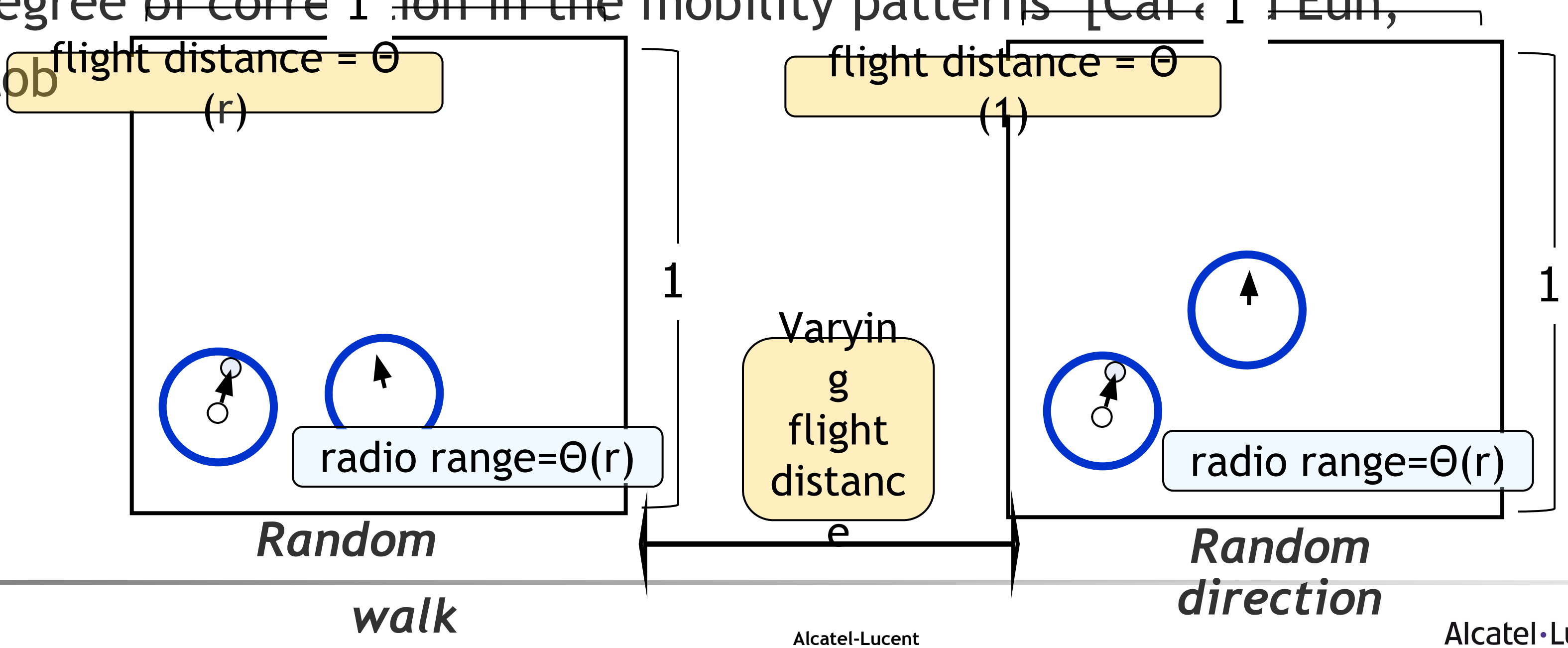
Inter-contact rate: λ ~ speed (v)*radio range (r) [Groenevelt, Perf'05]

- Random waypoint/direction (exp inter-contact time)

Flight distance (motion correlation):

- Ranging from radio radius Ω(r) to network width O(1)

Invariance property: avg inter-contact time does not depend on the degree of corre ion in the mobility patterns [Cai Eun, Mob



2-Hop Relay: DTN Routing

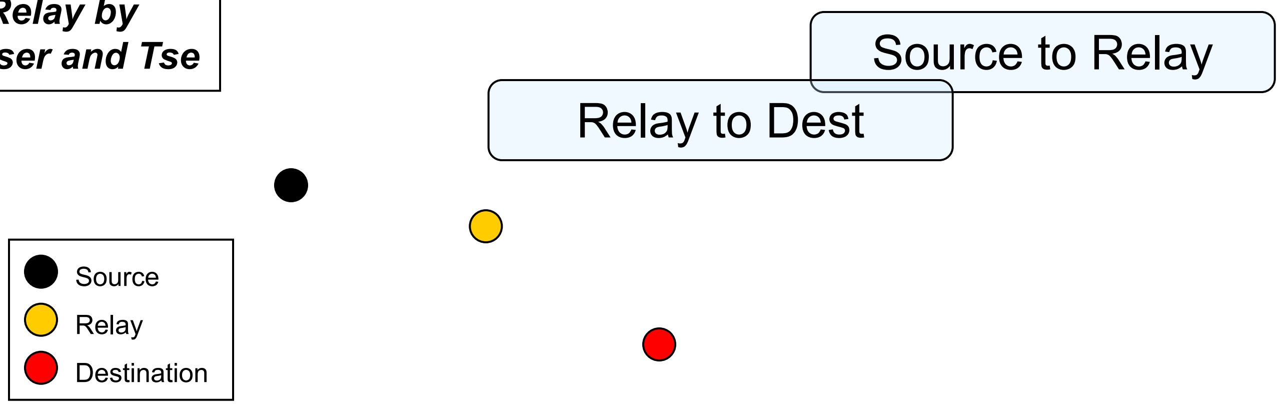
Each source has a random destination (n source-destination pairs)

2-hop relay protocol:

1. Source sends a packet to a relay node

2. Relay node delivers a packet to the corresponding receiver

2-hop Relay by Grossglauser and Tse



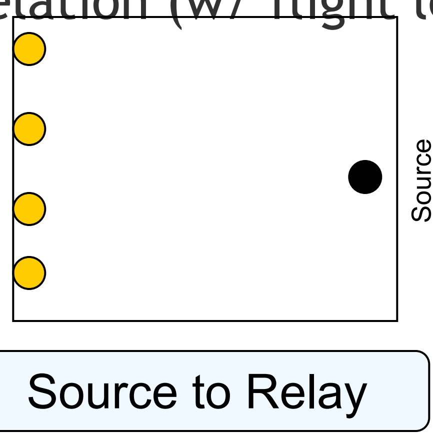
2-Hop Relay: Throughput Analysis

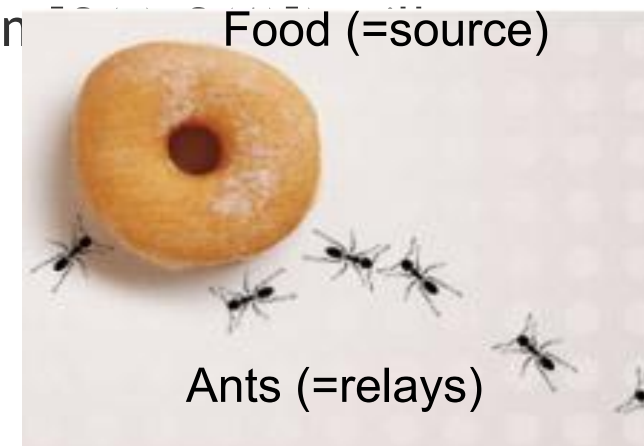
Intuition: avg throughput is determined by aggregate meeting rate (src⇔relay and relay ⇔ dest)

Two-hop relay per node throughput : Θ(nλ)

- Aggregate meeting rate at a destination: nλ
- Grossglauser and Tse's results: Θ(nλ)=Θ(1) when λ = 1/n (i.e., speed 1/√n, radio range 1/√n)

Motion correlation (w/ flight len ... s meeting rate





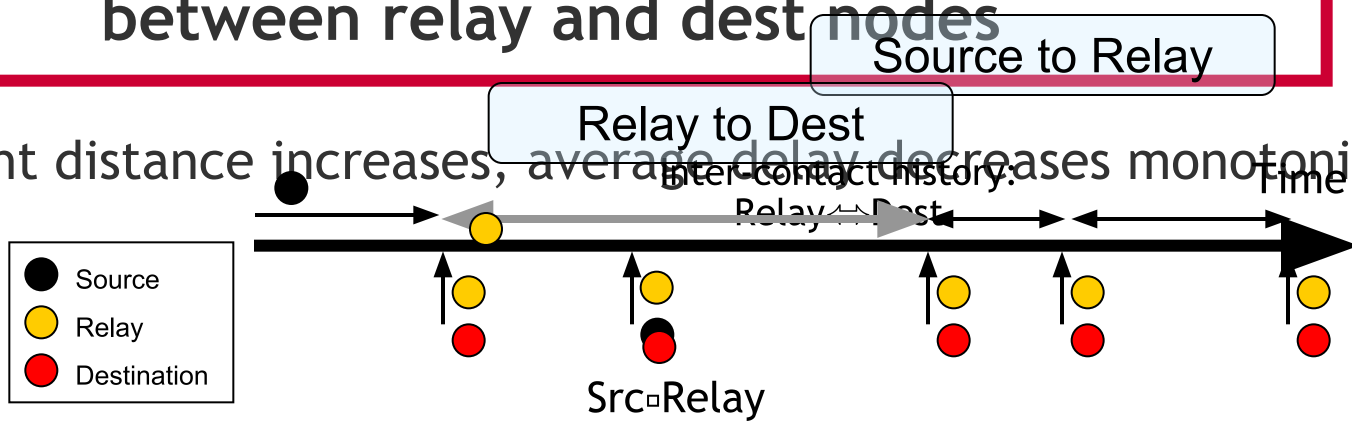
2-Hop Relay: Delay Analysis

Source to relay node (Dsr), and then relay to dest (Drd)

- **D_{sr}** = avg. inter-any-contact time to a random relay
- **D_{rd} = avg. residual inter-contact time (relay ⇔ dest)**
  - Mean residual inter-contact time ($\mathbf{D_{rd}}$) = $E[T^2] / 2E[T]$
    - >> T is a random variable for inter-contact time

Inspection paradox (length bias): source tends to sample a longer inter-contact interval between relay and dest nodes

- As flight distance increases, average delay decreases monotonically

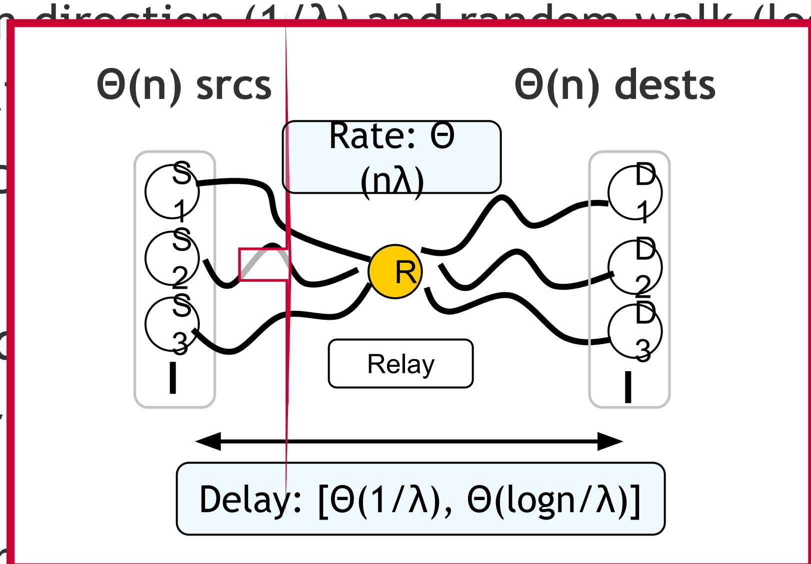


2-Hop Relay: Buffer Requirement

Little's law: buffer = (rate) x (delay)

Required buffer space per node: B = [Θ(n), Θ(nlogn)]

- Rate*delay = Θ(nλ)* [1/λ, logn/λ] = **[Θ(n), Θ(nlogn)]**
  - Recall: random direction (1/λ) and random walk (logn/λ)
- Motion correla
- Correlation inc



Impact of limited

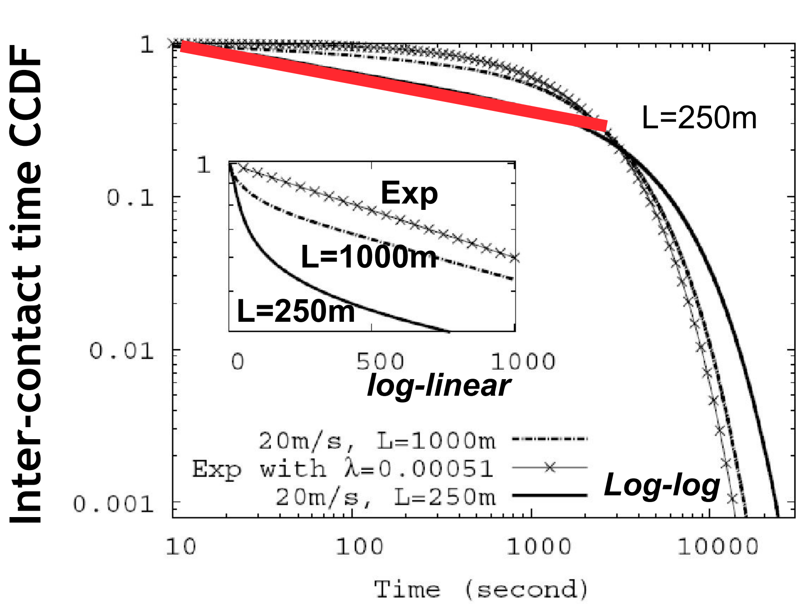
- Limited buffer ... y shared by *all* sources
- Relay node car ... th prob. K/B
- Throughput per source = Θ(nλ*K/B)

Simulation: Throughput

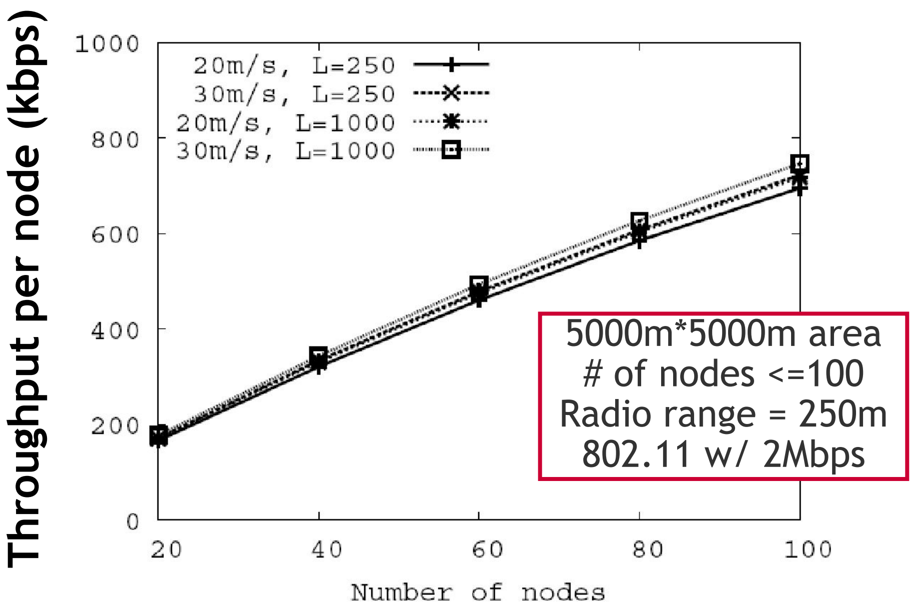
Degree of correlation via average flight distance L

- L=250m ▫ high correlation ⇔ power law head + exponential tail
- L=1000m ▫ low correlation ⇔ almost exponential

Throughput is independent of the degree of correlations



CCDF of inter-contact time (20m/s)



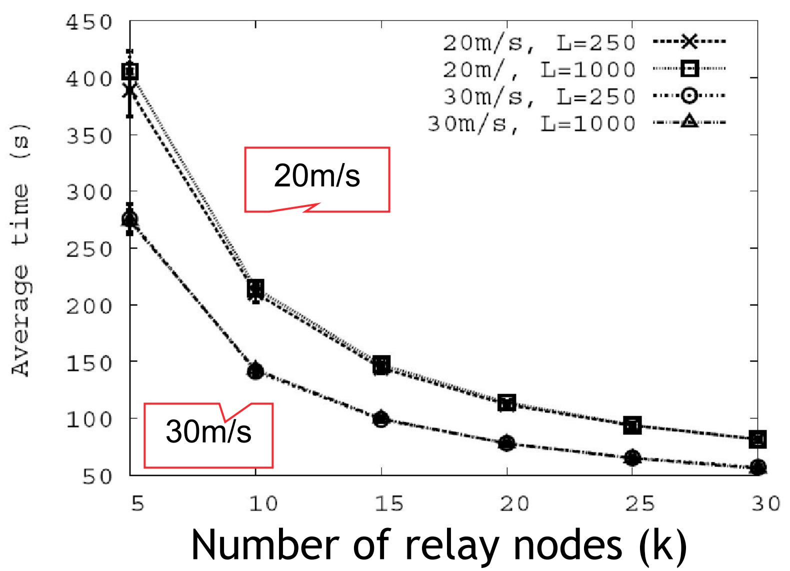
Average throughput per node as a function of # nodes

Simulation: Inter-any-contact Time

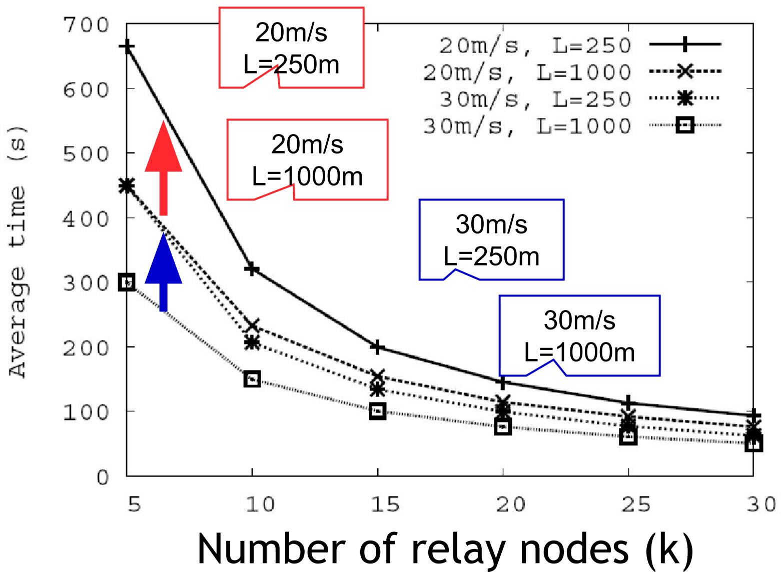
Inter-any(k)-contact time: inter-contact time to *any of k nodes*

Invariance property: avg inter-contact time is independent of correlation

Residual inter-contact time: source probes a random point of the inter-meeting times between relay and destination



Average Inter-contact time

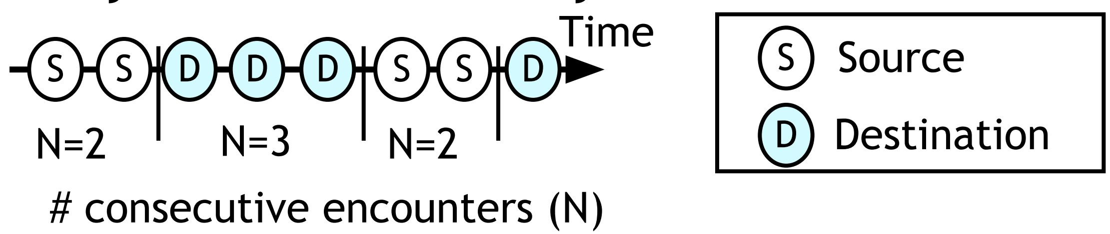


Average residual inter-contact time

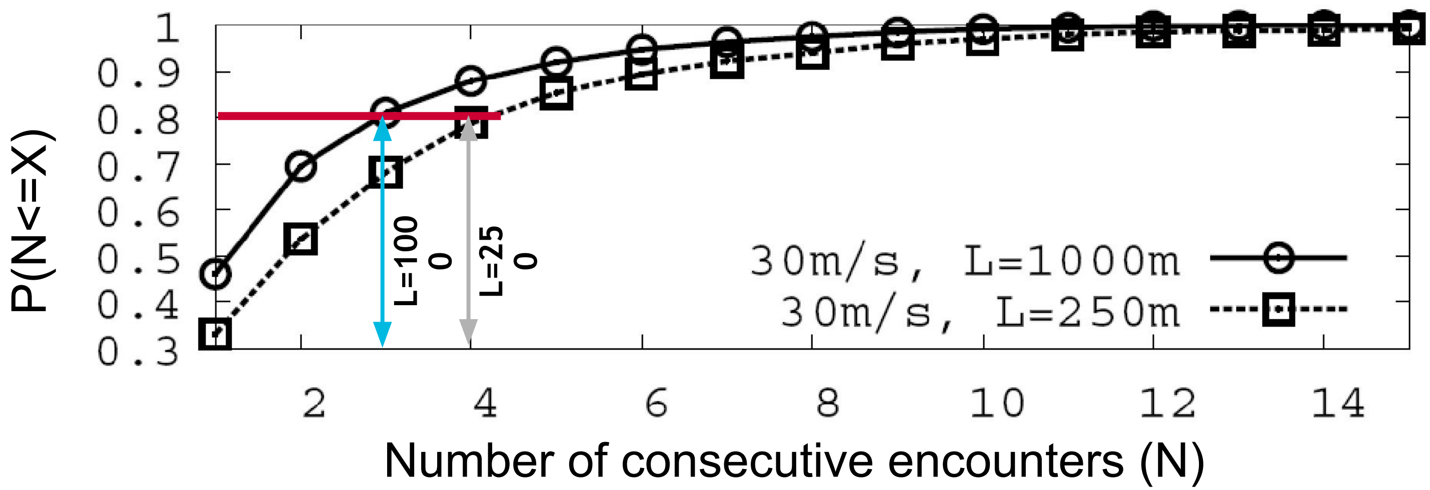
Simulation: Buffer Utilization

Burstiness of relay traffic increases with the degree of correlation

Relay node's contact history



Cumulative dist of # consecutive encounters



Conclusion

Impact of correlated motion patterns on DTN scaling properties

DTN model: inter-contact rate + motion correlation via flight distance

- Flight distance of $\Omega(r)$; i.e., min travel distance ~ one's radio range
- Considered mobility ranges from Random Walk to Random Direction

Main results:

- Throughput is independent of motion correlation
- Delay monotonically increases with the degree of correlation
- Buffer requirement also increases with the degree of correlation
- Correlation increases burstiness of relay traffic

Future work:

- Applying results to DTN multicast scenarios
- Scaling properties of inter-domain DTN scenarios