On the capacity of mobile ad hoc wireless networks

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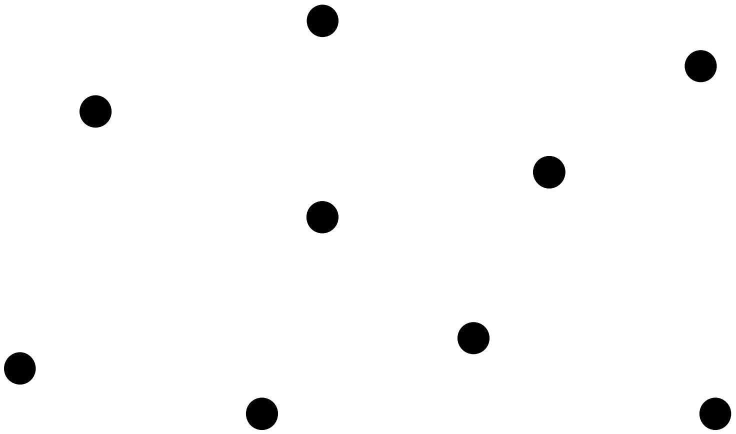
Outline

- Introduction and motivation
- Capacity for networks with finite number of nodes
- Asymptotic capacity for networks with infinite number of nodes
  - for heterogeneous nodes with restricted mobility
  - for “street”-like mobility

Introduction

- The sad Gupta-Kumar result:

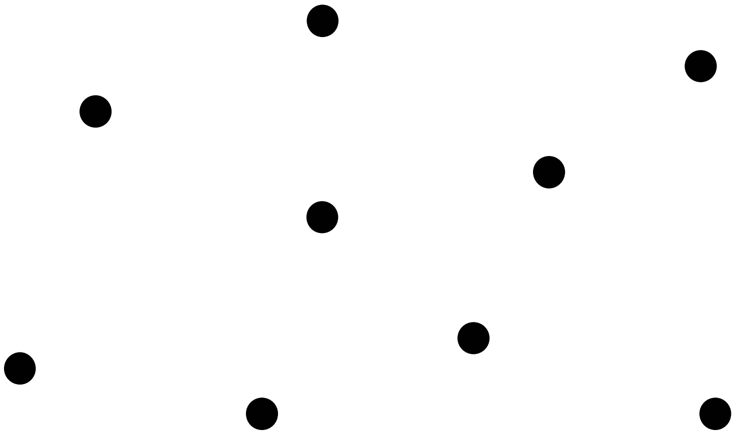
In static ad hoc wireless networks with n nodes, the per-node throughput behaves as $O\left(\frac{1}{\sqrt{n}}\right)$



P. Gupta, P.R. Kumar, **The capacity of wireless networks**, *IEEE Trans. on Information Theory*, March 2000

Introduction

- The happy Grossglauser-Tse result:
  - In mobile ad hoc wireless networks with n nodes, the per-node throughput remains constant $\Theta(1)$
    - o assumption: uniform distribution of each node presence over the network area



M. Grossglauser and D. Tse, **Mobility Increases the Capacity of Ad Hoc Wireless Networks**, *IEEE/ACM Trans. on Networking*, August 2002

Introduction

- Node mobility can be exploited to carry data across the network
  - Store-carry-forward communication scheme

- Drawback: large delays (minutes/hours)
  - Delay-tolerant networking

Mobile Ad Hoc (Delay Tolerant) Networks

- Have recently attracted a lot of attention
- Examples
  - pocket switched networks (e.g., iMotes)
  - vehicular networks (e.g., cars, buses, taxi)
  - sensor networks (e.g., disaster-relief networks, wildlife tracking)
  - Internet access to remote villages (e.g., IP over usb over motorbike)
- Key issue: how does network capacity depend on the nodes mobility pattern ?

The general (unanswered) problem

- What properties in the mobility pattern of nodes allow to avoid the throughput decay of static networks ?

- What are the sufficient conditions to obtain $\Theta(1)$ per-node throughput ?

- Are there intermediate cases in between extremes of static nodes (Gupta-Kumar '00) and fully mobile nodes (Grossglauser-Tse '01) ? Under which conditions ?

Our work

- capacity for arbitrary networks with finite number of nodes
  - definition of contact graph on which computing the maximum capacity
- asymptotic capacity for networks with infinite number of nodes
  - application to a class of mobile networks comprising heterogeneous nodes and spatial inhomogeneities
    - not anymore uniform spatial distribution of each node over the area

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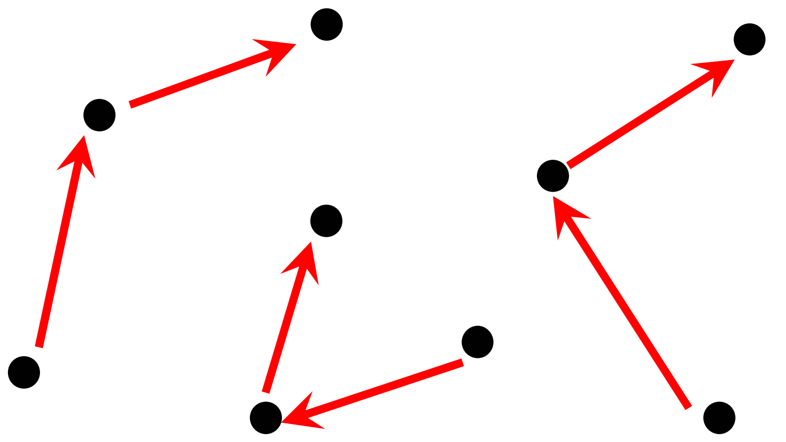
Arbitrary networks with finite number of nodes

- Assumptions:
  - n nodes moving according to a stationary and ergodic mobility process (possibly correlated among the nodes)
  - A source node s generates traffic for destination d according to a stationary and ergodic process with rate λ_{sd}
  - Transmissions between pairs of nodes occur at fixed rate r
  - At any given time, the instantaneous nodes positions allow to identify the "transmission configurations" that can be scheduled successfully according to some interference model



One possible transmission configuration

Another possible transmission configuration

Arbitrary networks with finite number of nodes

Main result:

- the maximum capacity (in networking sense) of a mobile wireless network depends on the mobility process only through the joint stationary distribution of nodes over the area
  - details on how nodes move (change of speed, direction, group movements) have no impact on network capacity

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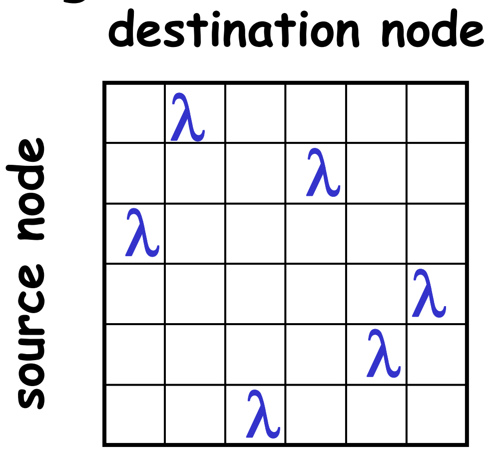
Assumptions

- n nodes moving over closed connected region
- independent, stationary and ergodic mobility processes
- uniform permutation traffic matrix: each node is origin and destination of a single traffic flow with rate $\lambda(n)$ bits/sec

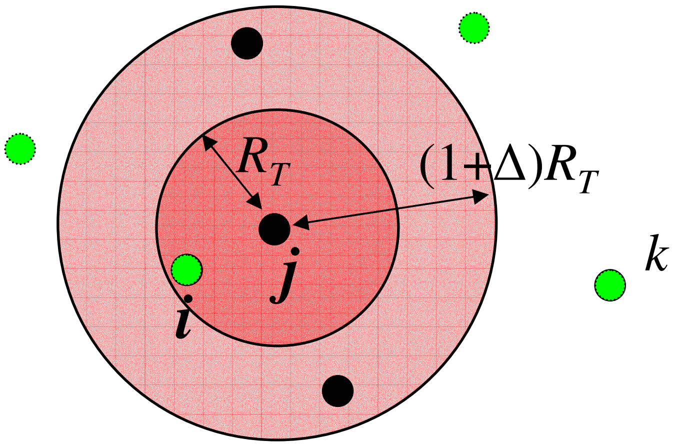


- all transmissions employ the same nominal range or power
- all transmissions occur at common rate r
- single-radio, omni-directional antennas
- interference described by protocol model (next slide)

Protocol Model

- Let d_{ij} denote the distance between node i and node j, and R_T the common transmission range
- A transmission from i to j at rate r is successful if:
  - $d_{ij} < R_T$
  - $d_{kj} > (1 + \Delta)R_T$

  for every other node k simultaneously transmitting



Asymptotic capacity

- We say that the per-node capacity is $\Theta(\lambda(n))$ if there exist two constants c and c' such that

$$\lim_{n\to\infty} \Pr\{c\lambda(n) \text{ is sustainable}\} = 1$$

$$\lim_{n\to\infty} \Pr\{c'\lambda(n) \text{ is sustainable}\} < 1$$

  - sustainable means that the network backlog remains finite

- Equivalently, we say that the network capacity in this case is $\Theta(n\lambda(n))$

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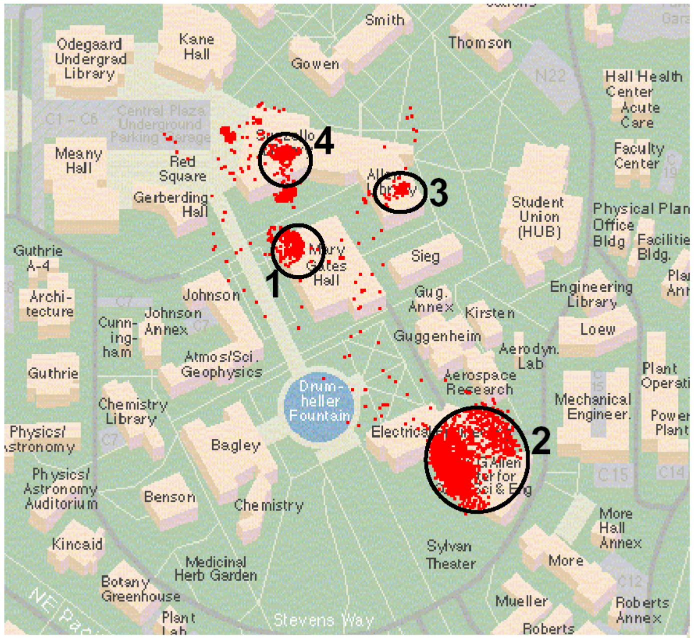
A realistic mobility model for DTNs

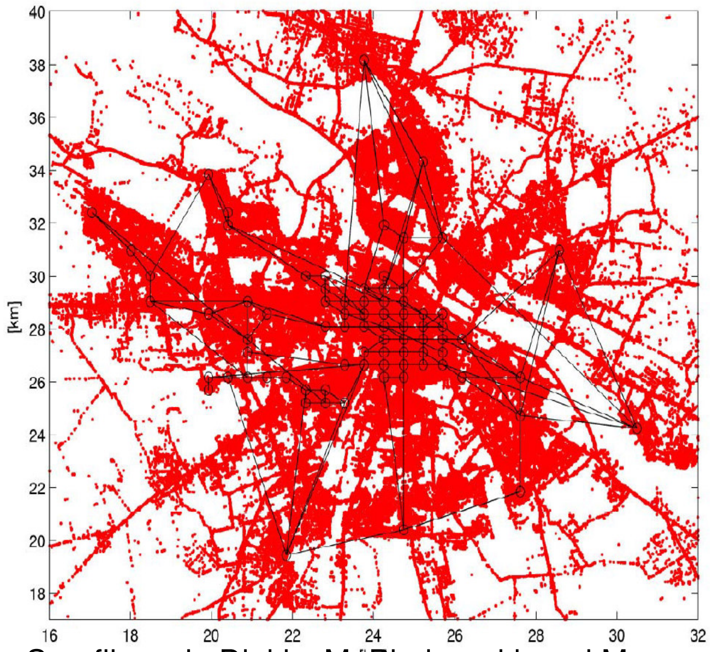
- Realistic mobility processes are characterized by :

Restricted mobility of individual nodes:



From: J.H.Kang, W.Welbourne, B. Stewart, G.Borriello, **Extracting Places from Traces of Locations**, *ACM Mobile Computing and Communications Review*, July 2005.

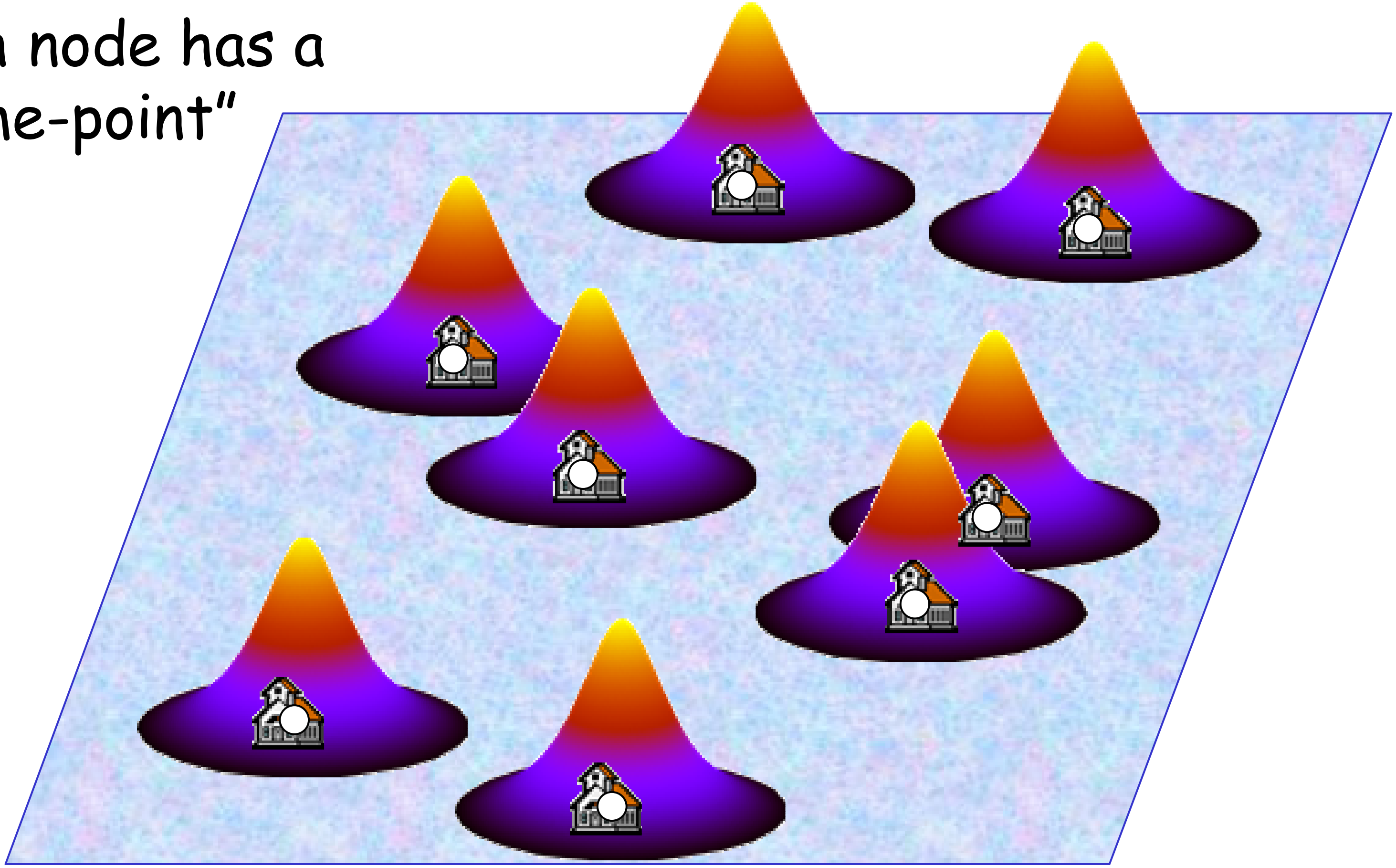
Non-uniform density due to concentration points



From: Sarafijanovic-Djukic, M. Piorkowski, and M. Grossglauser, **Island Hopping: Efficient Mobility-Assisted Forwarding in Partitioned Networks**,, *IEEE SECON 2006*

Heterogeneous nodes with restricted mobility

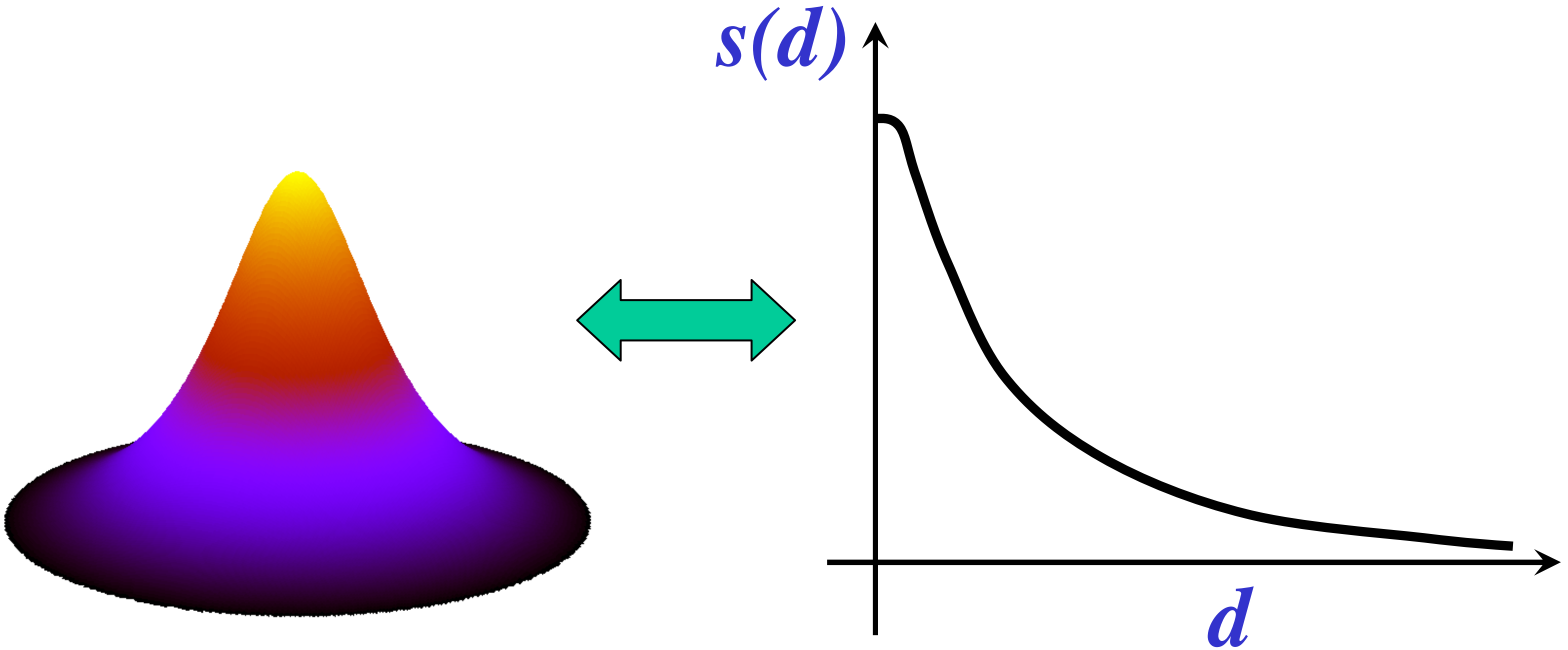
Each node has a "home-point"



… and a spatial distribution around the home-point

Restricted mobility

- The shape of the spatial distribution of each node is according to a generic, decreasing function $s(d)$ of the distance from the home-point

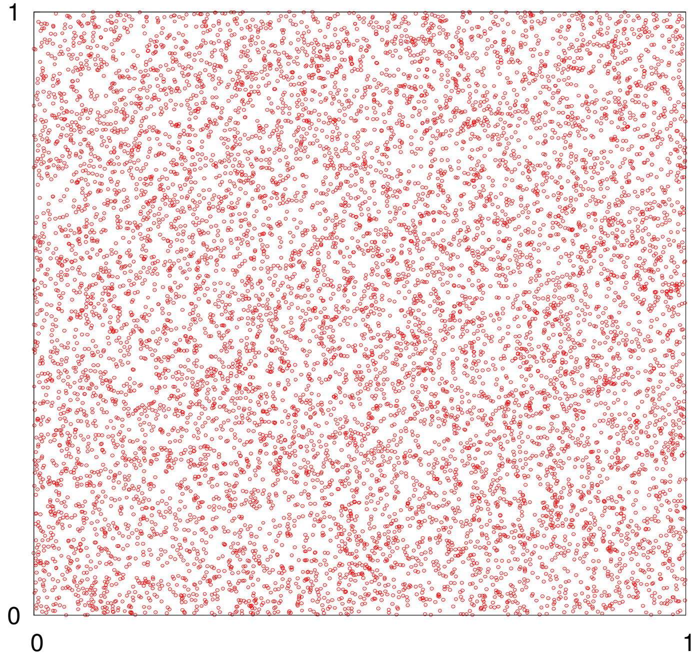


Anisotropic node density (clustering)

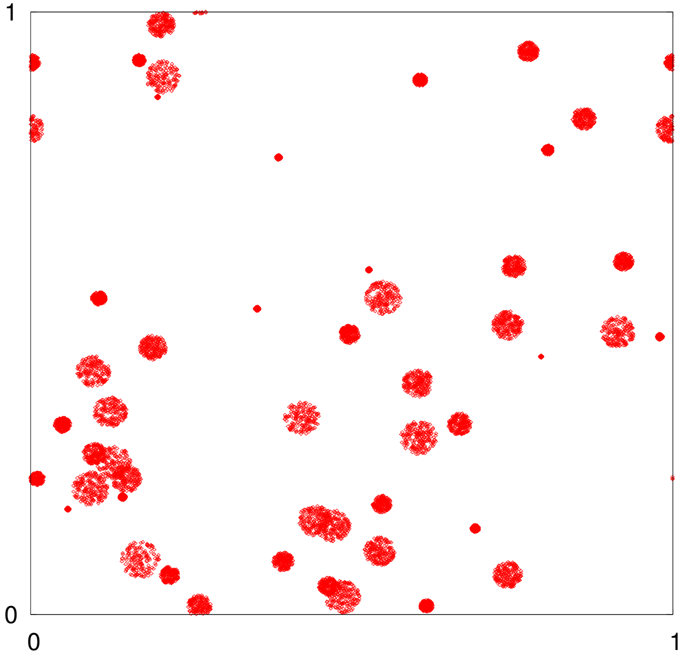
➢ Achieved through the distribution of home-points

Uniform model: home-points randomly placed over the area according to uniform distribution

Clustered model: home-points randomly assigned to $m = n^{\nu}$ clusters uniformly placed over the area. Home-points within disk of fixed radius from the cluster middle point

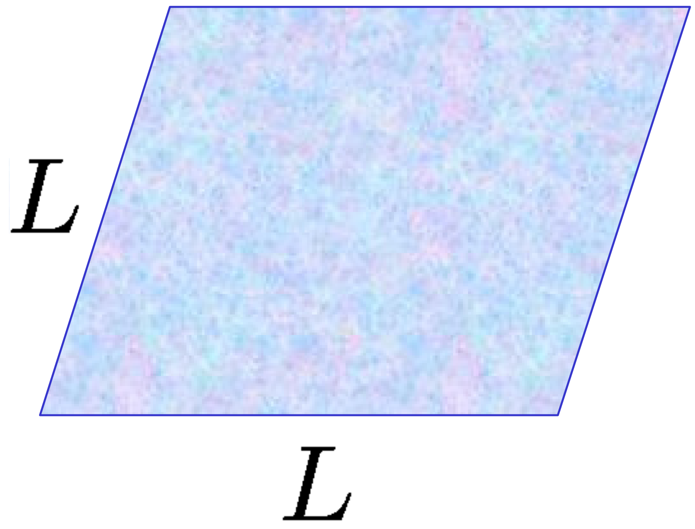


n = 10000



Scaling the network size

10 nodes……100 nodes…..1000 nodes

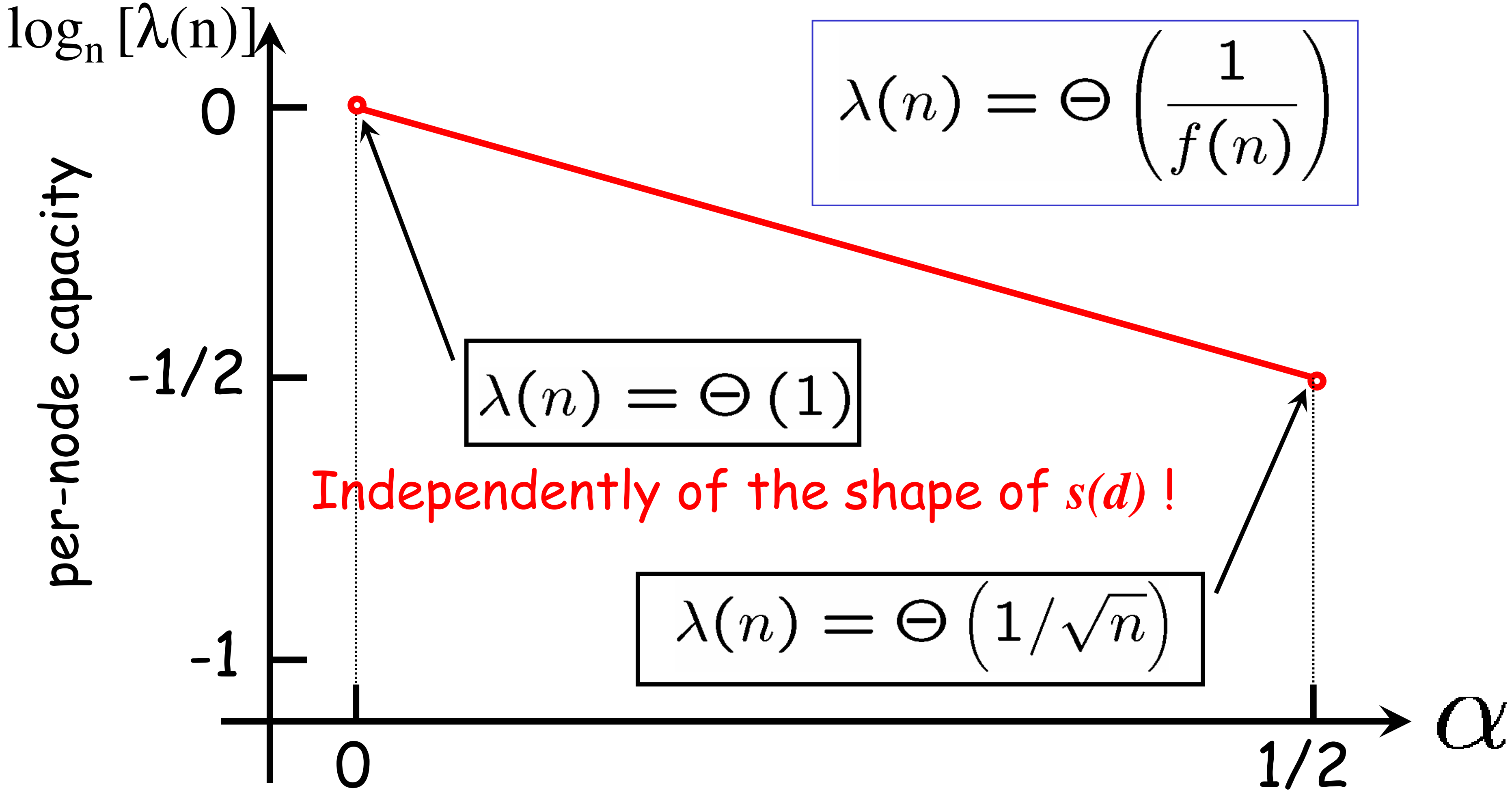


α=0: node density → ∞
α=1/2: node density const

We assume that: $L \sim f(n) = n^{\alpha} \quad \alpha \in [0, 1/2]$

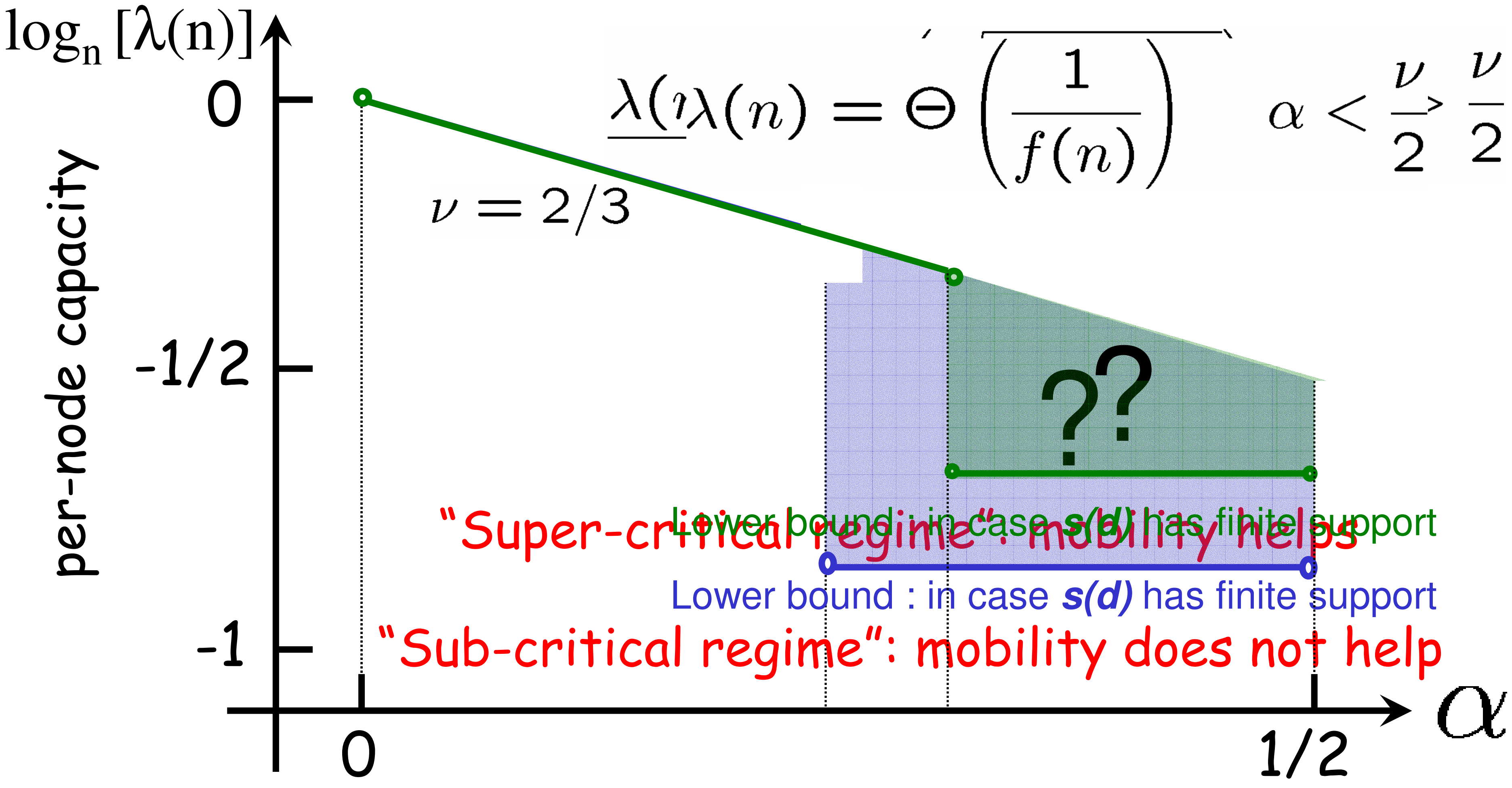
Moreover: node mobility process does not depend on network size

Asymptotic capacity for uniformly-located home-points



Recall: $L \sim f(n) = n^{\alpha} \quad \alpha \in [0, 1/2]$

Asymptotic capacity for clustered home-points



Recall: #clusters $m = n^{\nu}$ $\nu \in [0, 1]$

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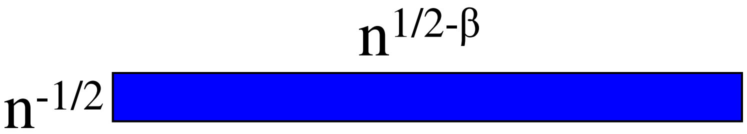
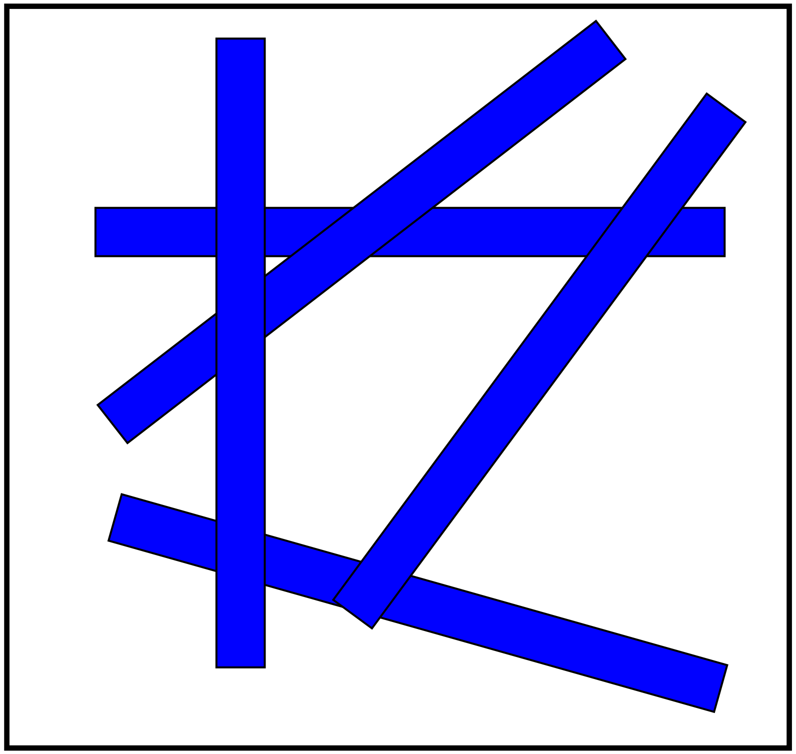
“Street”-like mobility

- Nodes constrained to move uniformly over rectangles of area $n^{-\beta}$ $(1/2 < \beta < 1)$, with minimum edge $n^{-1/2}$ and random orientation

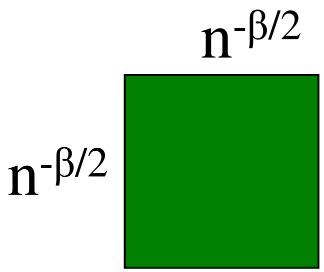




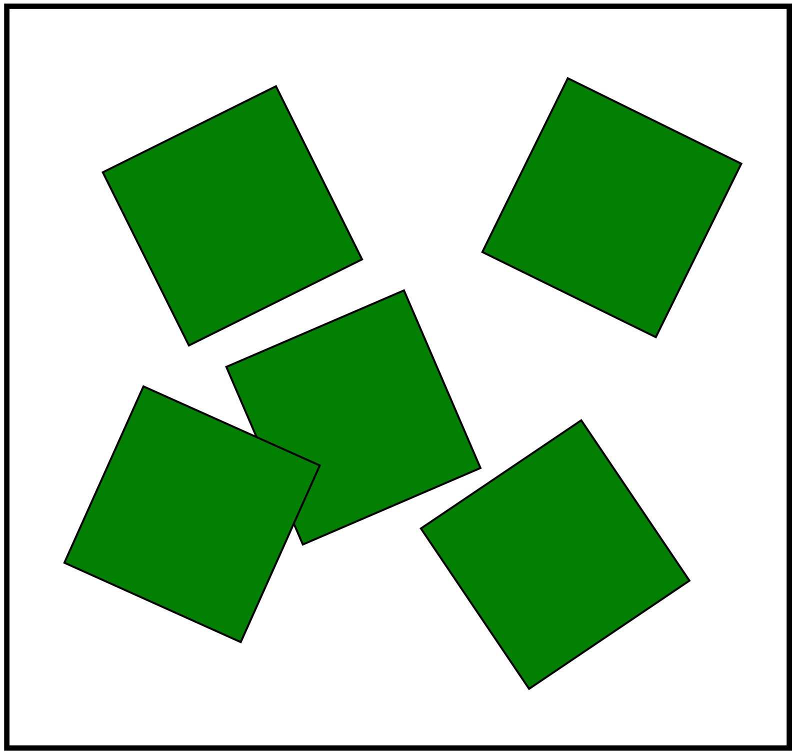
⇨ per node capacity $\lambda(n)=\Theta(n^{1/2-\beta})$

"Street"-like mobility

- Nodes contrained to move uniformly over squares of area $n^{-\beta}$ $(1/2 < \beta < 1)$ and random orientation



per-node capacity
$\lambda(n)=\Theta(n^{-\beta/2})$
worst than the other case



➢ **In general, network capacity can depend on the geometry of the space visited by the nodes**

Conclusions

- Some results of general validity for finite and infinite number of nodes
  - Mapping over maximum concurrent flow problem over geometric random graphs
- Application to a general class of mobile networks with heterogeneous nodes and clustering behavior
- Capacity computed for real DTN networks
  - vehicular mobility
    - DieselNet-Umass campus bus system
  - person mobility
    - attendees of Infocom'05 carrying imotes