Reviewing:

Mobility Increases the Capacity of Ad-hoc Wireless Networks

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Context

capacity of an ad-hoc wireless network

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capacity of an ad-hoc wireless network

- ad-hoc => does not rely on existing infrastructure such as access points
- routing is decentralized: each nodes participates in the routing by forwarding data
- routing decisions are made dynamically depending on the network connectivity (changing network topology)

Context

capacity of an ad-hoc wireless network

Capacity is measured in terms of total throughput (Mbit/s)

Context

The paper’s result apply to **delay-tolerant networks**.

Examples:

email, database synchronization, networks in space (where network topology changes frequently)

Non-Examples:

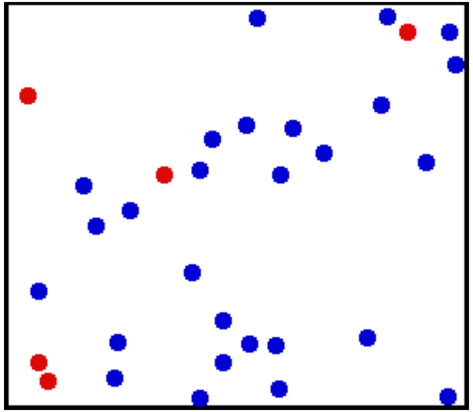
any real-time application (e.g. voice communications)

Problem

What is the **theoretical capacity** of an **ad-hoc, mobile, delay-tolerant network**?

How does it compare to the capacity of a stationary network?

Model - Overview



What's the scenario?

- n … number of mobile nodes
- trajectory as a stationary and ergodic process
- trajectories of different nodes are i.d.d. (independent and identically distributed)

Model - Session Model

- Each source has infinite number of packets to send its destination

Model - Transmission Model

- $X_i(t)$ … position of node i at time t
- beta … signal-to-interference ratio (SIR)
- $P_i(t)$ … transmit power of node i at time t
- gamma_{ij} … channel gain from node i to j → $\gamma_{ij}(t) := \frac{1}{|X_i(t) - X_j(t)|^\alpha}$
- alpha … constant for signal decay (~2)
- $P_i(t)*\text{gamma}_{ij}$ … received power at node j
- **Transmission between nodes i and j at time t is possible, if**

$$\frac{P_i(t)\gamma_{ij}(t)}{N_0 + \frac{1}{L}\sum_{k \neq i} P_k(t)\gamma_{ij}(t)} > \beta$$

Model - Transmission Model

The gist of it:

Transmission between two nodes (i,j) depends on

1. how close they are to each other
2. the interference from other nodes

$$\frac{P_i(t)\gamma_{ij}(t)}{N_0 + \frac{1}{L}\sum_{k\neq i} P_k(t)\gamma_{ij}(t)} > \beta$$

Model - The Scheduler

At time t, the scheduler decides

1. whether/to whom nodes will send packets
2. the power levels of those senders

The sender’s objective:

Maximize long-term throughput for each S-D pair.

Result - Fixed Nodes

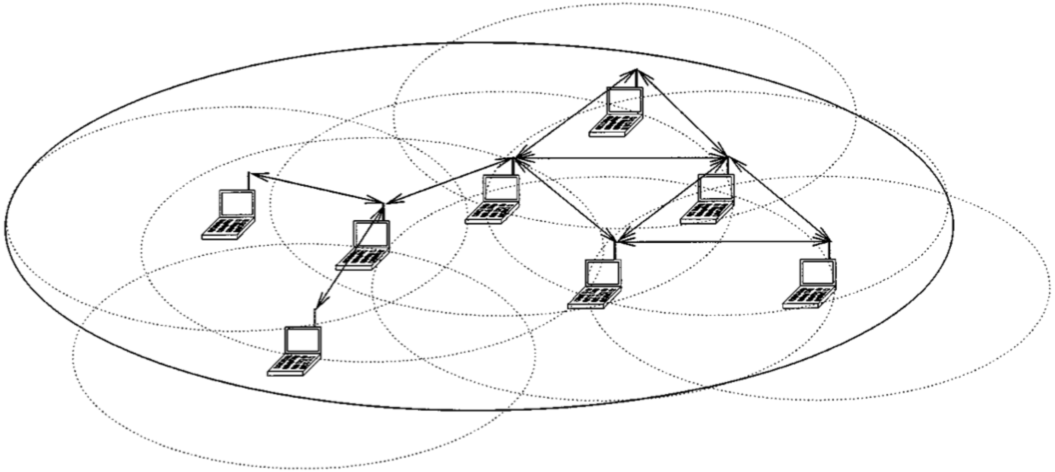
- Gupta and Kumar (2000), “The Capacity of Wireless Networks”
- Nodes are randomly located, but immobile
- Source & destination nodes selected at random
- Their main result:

  As n, number of nodes per unit area, increases the throughput per S-D pair decreases with complexity

  $$O(\frac{1}{\sqrt{n}})$$

Result - Fixed Nodes

- Reason: More nodes => more hops. Therefore, each nodes needs to dedicate more of its capacity to relaying packets travelling to other nodes.



Result - Fixed vs. Mobile Nodes

- Mobile nodes are **expected to meet eventually** (and we are tolerating delay).
- Can we improve the capacity of the network without any relaying?

Result - Fixed vs. Mobile Nodes

- Mobile nodes are **expected to meet eventually** (and we are tolerating delay).
- Can we improve the capacity of the network without any relaying?
- **No**, most of the time the distance between source and destination is large and simultaneous long-range communication is limited by interference.
- Throughput per S-D pair goes to zero as $n^{-\frac{1}{1+\alpha/2}}$

Result - Mobile Nodes with Relaying

- **Goal**: Spread packets to intermediate nodes to increase the chance of short range hops between source and destination.
- **Question**: How many times does a packet have to be relayed to maximize throughput?

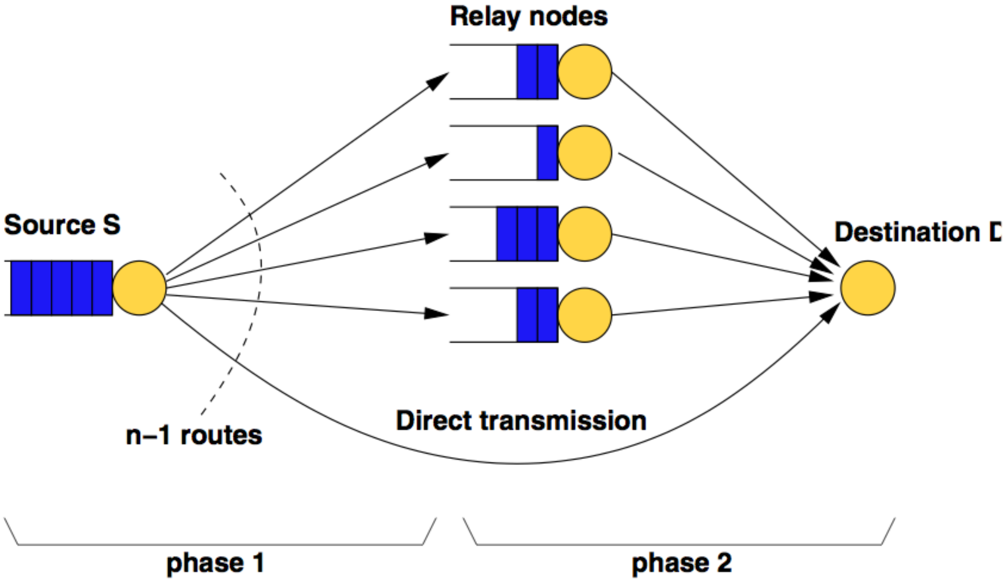
Result - Mobile Nodes with Relaying

Sender Policy Goal: Dispersion of Packets

- Randomly partition nodes into senders (S) and receivers (R)
- Each sender transmits packets to its nearest neighbor in R. As a function of n, **the number of pairs where the interference generated by others is sufficiently small to transmit successfully is O (n)** (see Theorem 3.4)

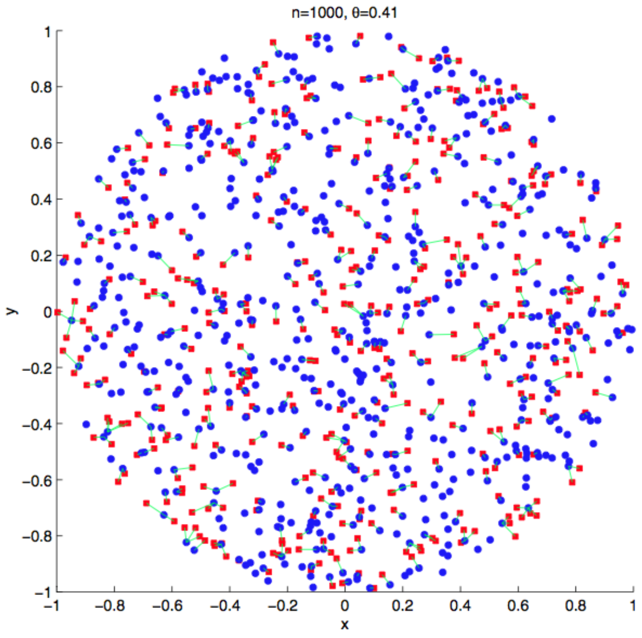
Result - Mobile Nodes with Relaying

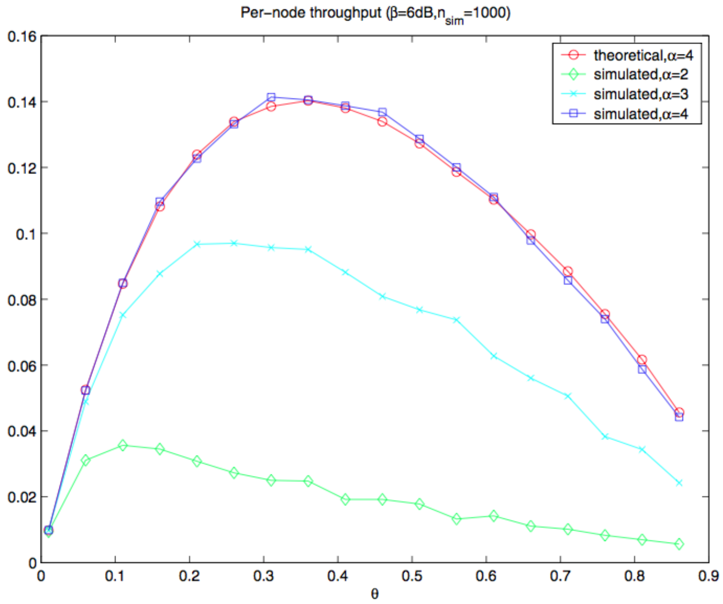
Algorithm (packet-view):



Result - Mobile Nodes with Relaying

Algorithm (overview):





Result - Mobile Nodes with Relaying

Analysis of Algorithm:

- The probability that two nodes i,j are selected as **feasible** by the sender policy is O(1/n) (Theorem 3.4)
- Summing over the n-2 two-hop routes and the 1 direct route, the **total average throughput per S-D pair is O(1)** (see theorem 3.5). This is the paper's **main result**.

Revisiting Assumptions

- Stationary and ergodic mobility (this is a simple type of mobility)
  - stationary => statistical properties constant over time
  - ergodic => *“ In practice this means that statistical sampling can be performed at one instant across a group of identical processes or sampled over time on a single process with no change in the measured result.”* - Wikipedia
- Mobility of nodes is independent
- Each node has infinite buffer
- Extreme delay tolerance. Focus is on throughput.

Conclusion I - Quantitative

Throughput per S-D pair in network with n nodes:

Fixed (Gupta and Kumar (2000))	Mobile No Relay	Mobile Single Hop Relay
$O(\frac{1}{\sqrt{n}})$	$O(n^{\frac{-1}{1+\frac{\alpha}{2}}})$ $= O(\frac{1}{\sqrt{n}}), \text{if } \alpha = 2$	$O(1)$

Conclusion II - Qualitative

- A single, random relay node is sufficient to yield constant throughput as the number of nodes increases.
- There's a tradeoff between between throughput and delay in mobile wireless networks.

Questions & Criticism

- This is an extreme view of the tradeoff between delay and throughput.
- Is there an upper bound on the delay of communications between two nodes?
  "Throughput-Delay Trade-off in Wireless Networks" (Gamal et al., 2004)
  $D(n) = O(\sqrt{n}/v(n))$