MOBILITY INCREASES THE CAPACITY OF AD HOC WIRELESS NETWORKS

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Wireless Network

Characteristic

- Time variation of channel strength
  - Interference from other nodes
  - Multipath fading
  - Distance attenuation

Unreliable transmission over certain channel

Solutions

Use diversity

- Obtained over time, frequency, etc.
- Provide multiple independent paths

This paper exploits multiuser diversity

Background

Ad hoc network

- No base stations
- Each node can be transmitter, receiver or relay
  - Paths are formed by nodes
- Strategy is important

Background

Previous work on ad hoc wireless network

by Gupta and Kumar

- Fixed nodes
- Uniform distribution
- Random selected S-D pair

Throughput per S-D pair decreases like $1/\sqrt{n}$

Not Scalable

Contribution of this paper

Allow nodes move independently and freely

Aim to keep throughput at a constant level

Scalability

Model

Assumption

- Nodes are i.i.d. and uniformly distributed
- Each node is a source as well as a destination
- S-D pairs are decided randomly

Requirement for successful transmission

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

In this paper: $\gamma_{ij}(t) := \dfrac{1}{|X_i(t) - X_j(t)|^\alpha}$

Model

Definition of feasible long-term throughput $\lambda(n)$

$$\liminf_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} M_i^T(t) \geq \lambda(n).$$

Consider only optimal strategy

Mathematical form

For fixed nodes

Theorem III-1 (Main Result 4 in [6]): There exists constants c and c' such that

$$\lim_{n\to\infty} \Pr\left\{\lambda(n) = \frac{cR}{\sqrt{n\log n}} \quad \text{is feasible}\right\} = 1$$

and

$$\lim_{n\to\infty} \Pr\left\{\lambda(n) = \frac{c'R}{\sqrt{n}} \quad \text{is feasible}\right\} = 0.$$

The average number of hops is of the order of $\sqrt{n}$

Reason?

The number of nodes increases

↓

Shorter communication range due to interference

↓

More relays

↓

Less efficient use of throughput

Hypothesis

Define transport capacity:

total distance traveled by all bits per unit time

If nodes can move freely

$\Downarrow$

Restrict the number of relays, keep transport capacity

$\Downarrow$

Throughput per S-D pair guaranteed

Mobile nodes without relaying

- Direct communication
- Communication range is restricted

$$\frac{P_i(t)\gamma_{i,j(i)}(t)}{N_0 + \frac{1}{L}\sum_{k\in\mathcal{S}(t),\, k\neq i} P_k(t)\gamma_{k,j(i)}(t)} \geq \beta.$$

$$\sum_{i\in\mathcal{S}(t)} |X_i(t) - X_{j(i)}(t)|^{\alpha} \leq B$$

$$B := 2^{\alpha}\pi^{-\alpha/2}\frac{\beta + L}{\beta}.$$

Mobile nodes without relaying

Theorem III-3: Assume that the policy is only allowed to schedule direct transmission between the source and destination nodes, i.e., that no relaying is permitted. If c is any constant satisfying

$$c > \left[2^{\alpha}\left(1+\frac{2}{\alpha}\right)\pi^{-\alpha/2}\frac{\beta+L}{\beta}\right]^{1/(1+\alpha/2)}$$

then

$$\Pr\left\{\lambda(n) = \mathrm{c}n^{-(1/(1+\alpha/2))}R \quad \text{is feasible}\right\} = 0$$

for sufficiently large n.

Still not scalable without relaying

Analysis

Reason?

- Probability of transmitter meeting receiver is low

Solution

- Using relays to improve the probability
- No data copies

Mobile nodes with relaying

Need more than one relay?

- Doesn’t raise probability of meeting destination

One relay is enough

Mobile nodes with relaying

- Split the packet stream to relays
- Relays transmit the packets to destination when possible

Ideal scenario

- All other nodes have packets from source
- Ever time slot a packet is delivered to destination

Transport capacity is high, relay number is low

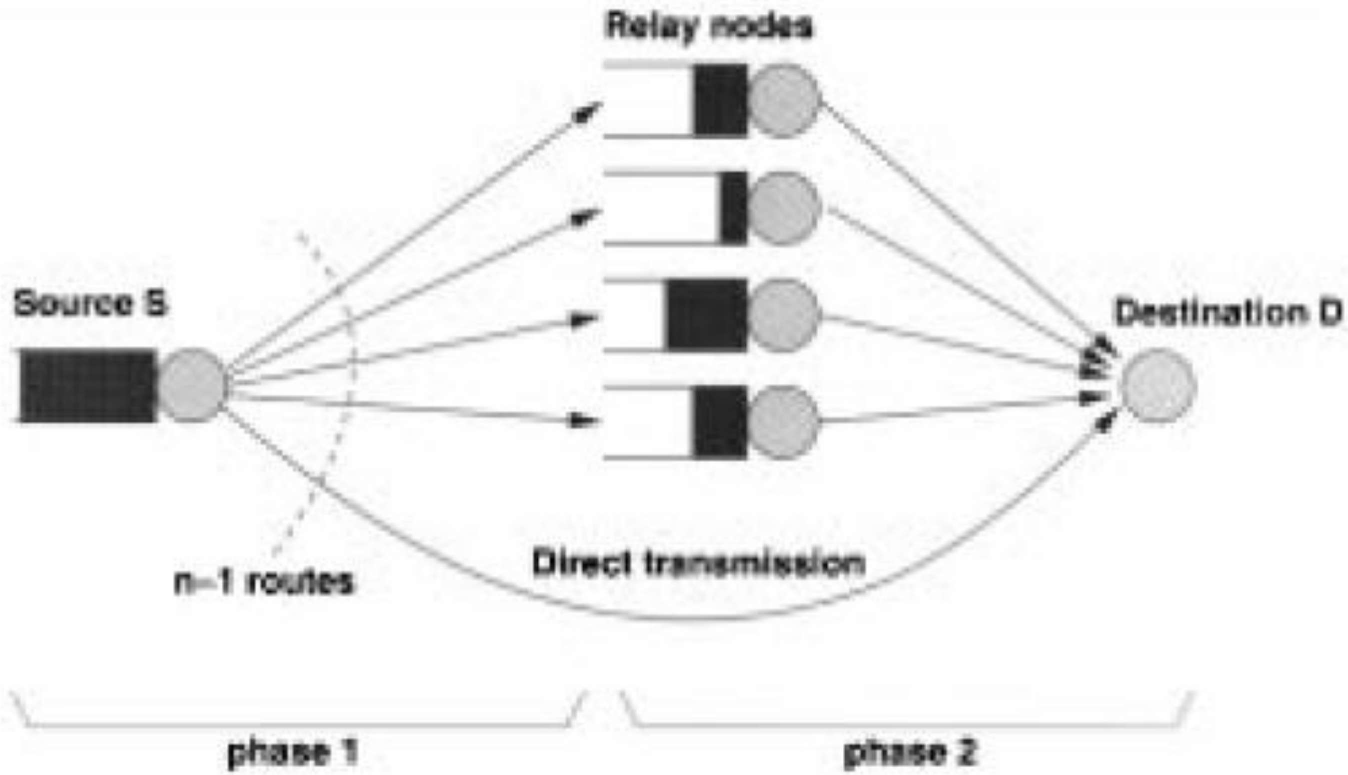
Throughput guaranteed

Mobile nodes with relaying

Realization

- Two phases
- In phase 1, source communicates with relays
- In phase 2, relays communicate with destination
- In both phase, source can communicate with destination
- In each phase, senders and receivers are selected through policy

Mobile nodes with relaying



Example

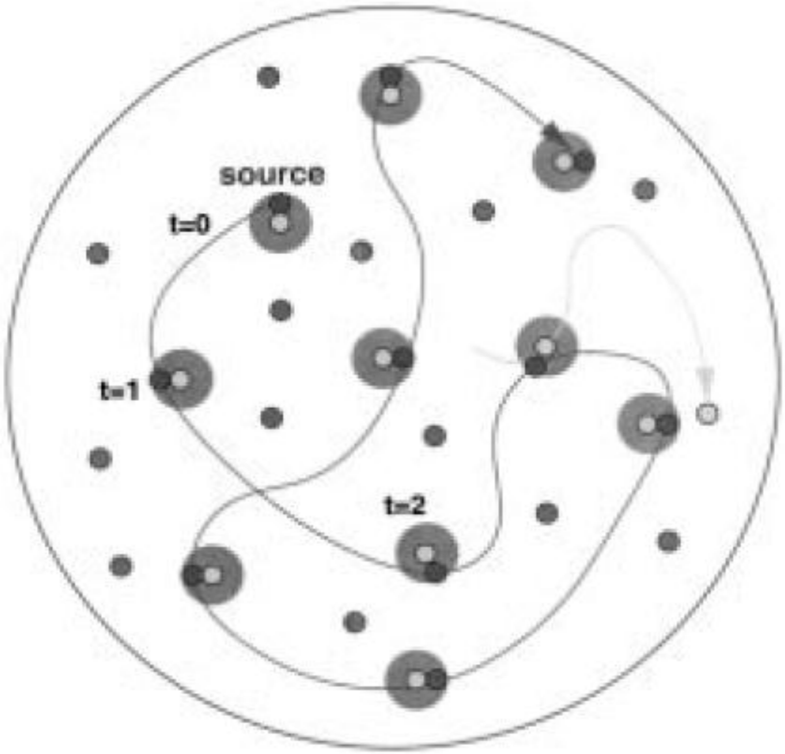


Fig. 1. In phase 1, each packet is transmitted by the source to a close-by relay node.

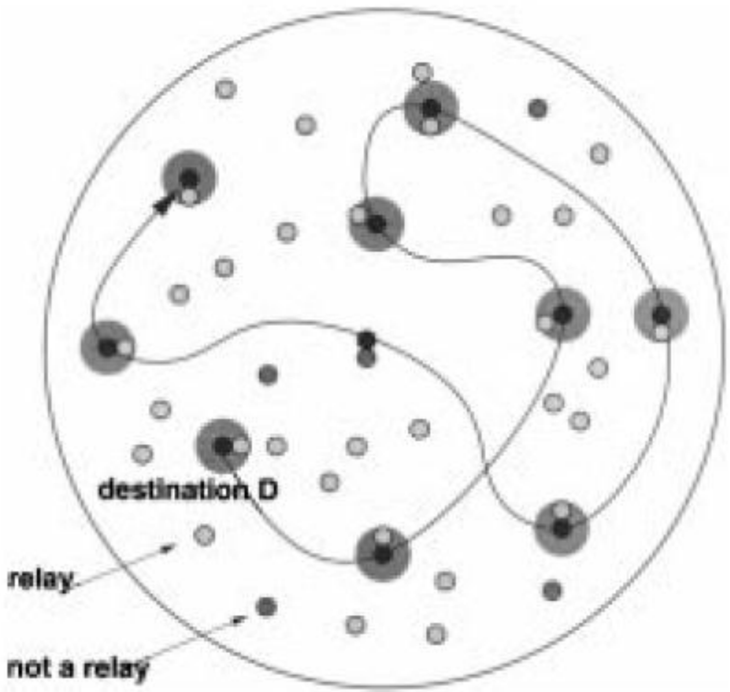


Fig. 2. In phase 2, a packet is handed off to its destination if the relay node is close by.

Proof

Theorem III-4: For the scheduling policy π, the expected number $\mathrm{E}[N_t]$ of feasible sender–receiver pairs is $\Theta(n)$, i.e.,

$$\lim_{n\to\infty} \frac{\mathrm{E}[N_t]}{n} = \phi > 0.$$

$\Theta(n)$ concurrent successful transmissions

Theorem III-5: The two-phased algorithm achieves a throughput per S–D pair of $\Theta(1)$, i.e., there exists a constant $c > 0$ such that

$$\lim_{n\to\infty} \Pr\{\lambda(n) = cR \quad \text{is feasible}\} = 1.$$

Constant level throughput per S-D pair

Essence of proof

Observation

- Received power at the nearest neighbour is of the same order as the total interference from $\Theta(n)$ number of interferers

Reason

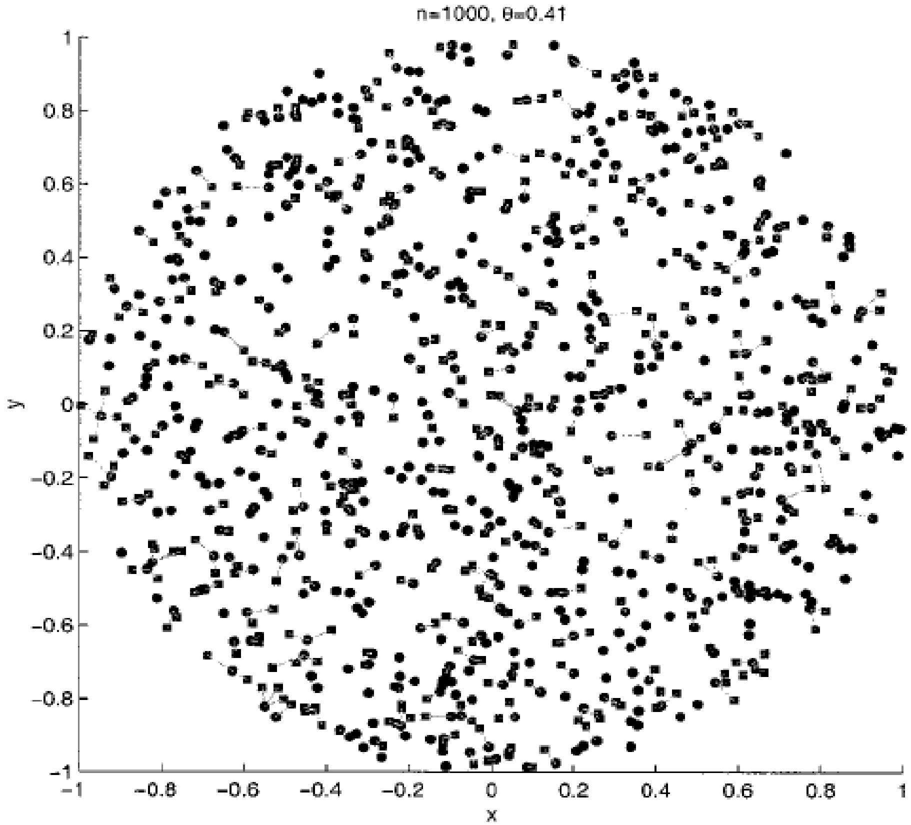
- If $W_1,\ldots,W_n$ are i.i.d. random variables, cdf F(w) decays slower than w^{-1} as $w \to \infty$, then the largest of them is of the same order as the sum

Distributed Implementation

- Model uses centralized scheduling
- Nodes can decide themselves
- Minor modifications
  - Give priority to phase 2
- Less throughput, but still in the same order

Simulations

Example network topology



Simulations

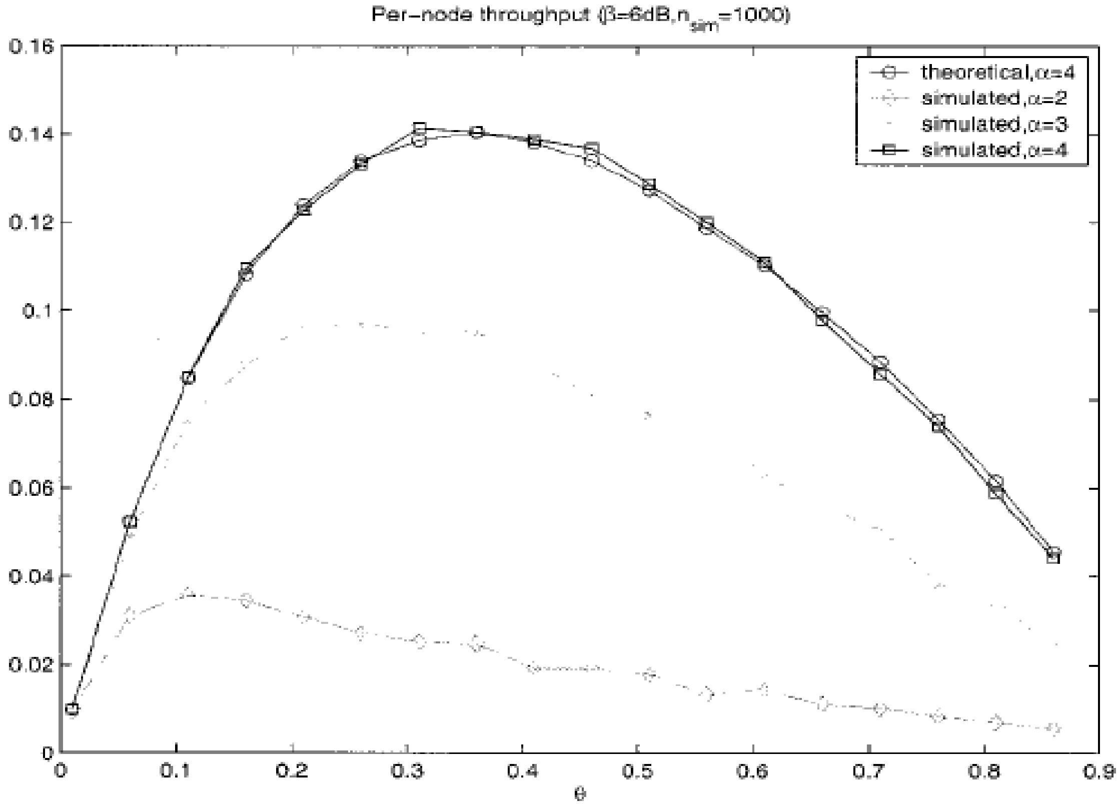
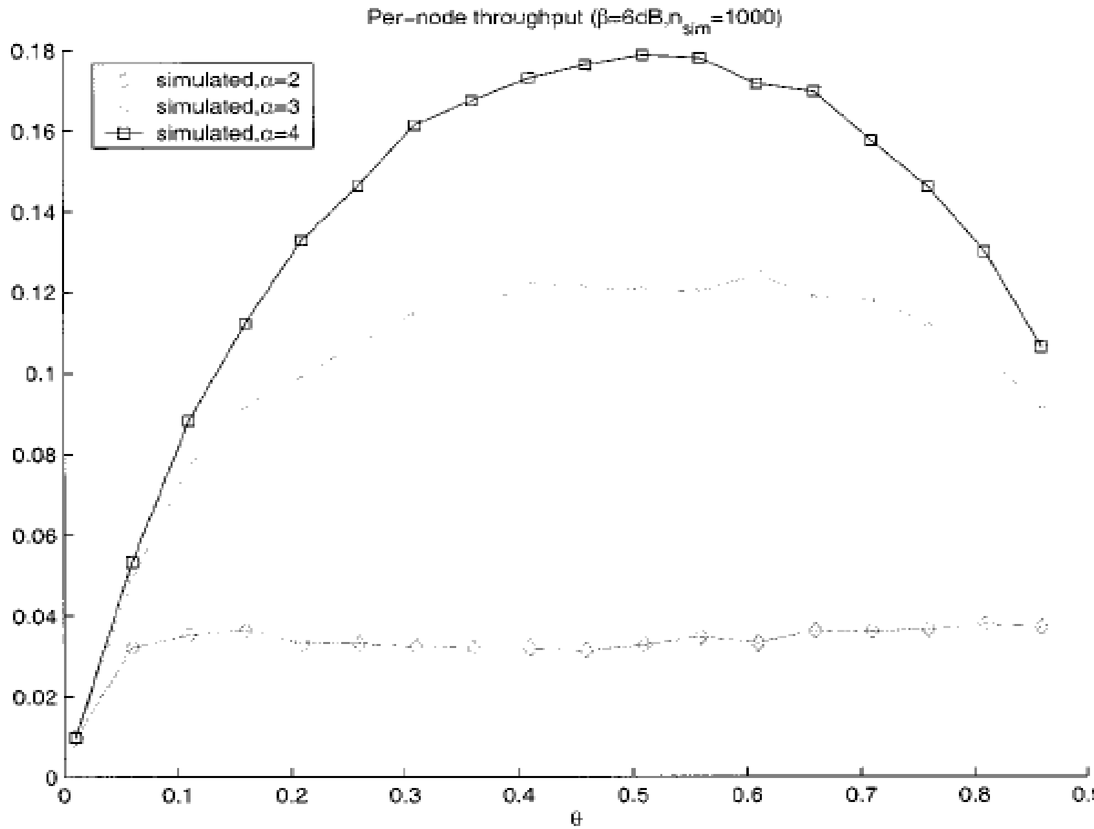


Fig. 6. The normalized per-node throughput, as a function of the sender density θ, for different values of α. For $\alpha = 4$, the throughput predicted by the model is also shown.

Throughput is affected by sender density

Simulations



Receiver-centric might provide better throughput

Discussion

Drawback

- Latency is high

Comparison

- With other path diversity techniques
- With delay tolerant forwarding

Discussion

Extension

- Constrained movement might still work

Contribution

- Provide chance to trade off between delay and throughput