Mobility Increases Capacity In Ad-Hoc Wireless Networks

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Introduction

- Challenges in wireless networks
  - Time variation of the channel strength
    - Multipath fading
    - Path loss via distance attenuation
    - Shadowing by obstacles
    - Interference from other users
  - Design impact throughout the layers
- What is a solution? → *Diversity*

Motivation

- Use of *diversity* to transfer the signal
  - Time diversity:
    - At different time instants
    - Interleaving of code bits, error correction
  - Frequency diversity:
    - Using several frequency channels or spread spectrum
  - Space diversity:
    - Over several different propagation paths
    - Multiple antennas
- This paper is focus on *Multiuser diversity*
  - A wireless network with multiple users
  - Introduced by Knopp and Humblet
  - Opportunistic user scheduling at either the transmitter or the receiver

Overview

- *Throughput*: Time average of the *number of bits per second* that can be transmitted by every node to its destination
- End-to-end delay is not a main issue
  - Delay tolerant applications: email, database synchronization, event notification
- Beyond existing cellular networks
  - No base station, multiple pairs of sources and destinations
- *Goal*:
  - Show that the long term *throughput* remains *constant* as the *number of users increases*

System Model

- Open disk of unit area (of radius $1/\sqrt{\pi}$) with n randomly placed nodes
- Let $X_i(t)$ is a location of the i^{th} user at time t
- At slotted time t, $P_i(t)$ is the transmit power of node i
- γ_{ij} be the channel gain from node i to node j
- L is the processing gain of the system, β is SINR threshold and N_o is background noise
- Node i transmits at rate R pkts/sec to node j

  if

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

Previous Work in Fixed Networks

- Gupta & Kumar (2000) – presented by Zhouija
  - Proposed model for studying the *capacity of wireless networks*
  - *Fixed* and randomly deployed nodes, random destination, packets are relayed
- Main result: Physical Model
  - 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

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

Intuition:
- As number of nodes ***n*** per unit area increases, the *throughput* per S-D pair *decreases approximately like 1/√**n***
- Pessimistic result on scalability as the *traffic rate per S-D pair goes to 0!*

Fixed vs. Mobile Networks

- Fixed: Long-range direct communication
  - Interference – packets are relayed
  - Transmission range decreases in order of $1/\sqrt{n}$
  - Number of hops increases in order of $\sqrt{n}$
  - Actual throughput per user pair is small
- Authors found that
  - In the presence of mobility, we can use multi-user diversity to guarantee constant throughput
  - Fraction of time two nodes of the order of $1/n$
  - Multiple distribution of a packet

→ Average throughput of S-D pair can be kept *constant* as n increases

Mobile Nodes *Without* Relaying

- Theorem 3.3: At time *t*, *S(t)* is the set of source nodes scheduled successfully. Then,

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

then

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

Intuition:
- For a large *n*, without relaying the achievable throughput per S-D pair goes to 0 at least as fast as $n^{-(1/(1+\alpha/2))}$
- Number of simultaneous long range communications is limited by *interference*

Mobile Nodes *With* Relaying

- Problem with direct transmission
  - Long range transmission → *interference limited*
- How can we improve throughput?
  - Avoid interference
  - Allow concurrent transmissions
  - *Constrain transmission to nearest neighbors*
    - Fraction of time order of 1/n
    - Vanishes for large n

    → *Distance-limited*

Mobile Nodes *With* Relaying

- Solution:
  - Multi-user diversity
  - Spread out packets to a large number of relay nodes
  - Relay nodes temporary buffer the packets until final delivery to destination
  - In steady state, every node has a packet **from** every other node, and every node has a packet **to** every other node
  - So, any S-D pair always has a packet to send → not true in direct transmission

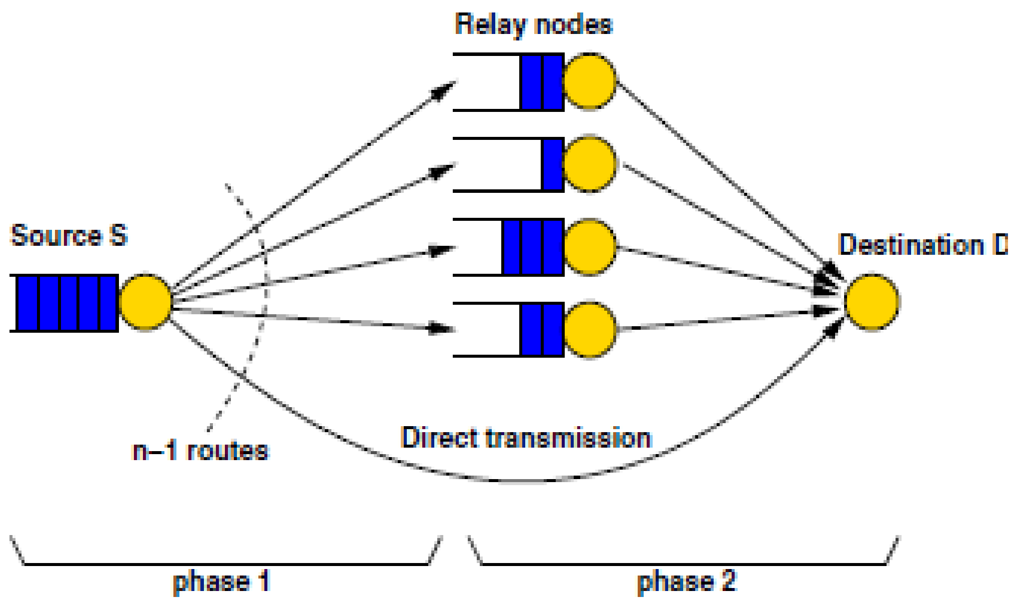
Number of Hops

- How many times a packet has to be relayed? → *Once*
  - Node location processes $X_i(t)$ are independent, stationary, and ergodic
  - *Probability* for an arbitrary node to be scheduled to receive a packet from a source *S* is *equal for all nodes* and *independent of S*
  - No packet is transmitted more than *two hops*

Schedule Policy (π)

Apply a 2-phase interleaved scheduling policy:

1) Source sends to relay (or destination) at odd time-slots
2) Relay (or source) sends to destination at even time-slots



Theorem 3.4

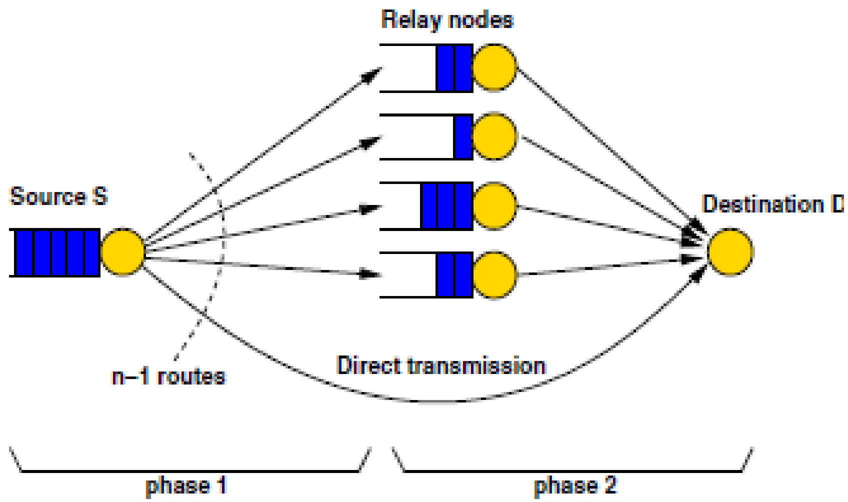
- Let proposed scheduling policy is π. Let θ ϵ (0,1)
- Let number of random sources, $n_s = \theta n$ and the remaining n_R are potential receivers
- Transmit power $P_i(t) = 1$
- Let N_t be number of successful transmissions from source to its neighbor

Result:

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

Intuition:
- For the scheduling policy π, the expected number $E[N_t]$ of feasible sender-receiver pairs is O(n).
- Furthermore, for two arbitrary nodes *i* and *j*, the probability that (*i*,*j*) is scheduled as a sender-receiver pair is $O(1/n)$ – Proof is based on interference analysis

Throughput Analysis



- Throughput over direct route is *O(1/n)*
- Other (n-2) routes also have throughput *O(1/n)*
- Total average throughput per S-D pair is *O(1)* → main result of the paper
- Overall, throughput is *O(n)* as *n* increases

Main Result: Theorem 3.5

- The two-phased algorithm achieves a throughput per S-D pair of *O(1)* i.e there exists a constant c > 0 such that

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

Numerical Results

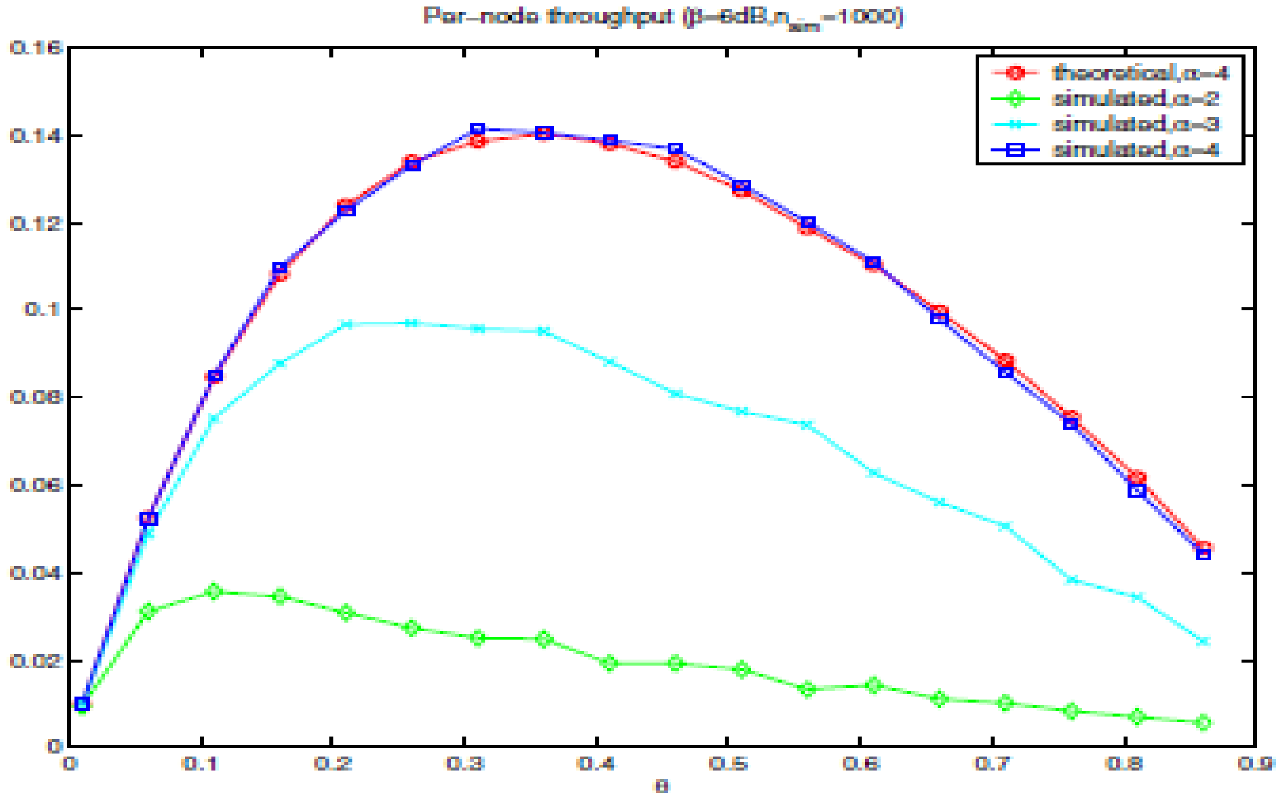


Figure 4: The normalized per-node throughput, as a function of the sender density θ, for different values of α. For $\alpha = 4$, the throughput predicted by the model is also shown.

Sender Centric vs. Receiver Centric Approach

- Sender centric – sender selects the closet receiver to send to
- Receiver centric – receiver selects the closet sender from which to receive
- Receiver centric is better because the signal received would always be *strongest*
- SIR for receiver centric is smaller on average than the sender centric

Conclusion

- \+ Spreading of traffic using *relays* and *mobility* to exploit *multiuser diversity*
- \+ Two hop routes are used to achieve *constant asymptotic throughput*
- — Results are based on an idealized setup
- — Assumes a central scheduler
- — Does not address delay problem, tradeoff in capacity and delay