Mobility Increases the Capacity of Ad Hoc Wireless Networks

Matthias Grossglauser and David N. C. Tse

Presented by Laurie James

Background - problem

Wireless networks are inherently limited by:

- Multipath fading;
- Path loss from changing relative distances;
- Object shadowing;
- De/constructive interference from other users.

Together, these are `Short-Scale Fading'.

Thus, wireless communication over a given path is unreliable.

Background – multi-users

- This assumes a direct, point-to-point link between sender and receiver.
- If we have multiple users, each of their paths to the base station fade *independently.*
- So, to maximise throughput:
  - At any one time, only transmit to/from the user with the best channel.

Background - diversity

Fading countered by introducing *diversity* into the network.

Core concept:

- If a given path has some probability of being unusable, add more paths until the probability of *all* paths being unusable is low.

Typical, previous methods of diversity:

- More antennas;
- More base stations;
- Multipathing - broadcast over multiple frequency channels (CDMA).

Background – Gupta & Kumar

Ad-hoc network:

- Each node performs routing, forwarding other nodes' packets.
- Paths are *dynamic*.

Gupta and Kumar modelled throughput in fixed ad-hoc networks.

- In many-node networks, long-range point-to-point communications are impossible (interference).
- So transmit data via relaying.

Their network has a random distribution of immobile nodes, each node:

- Is a sender – has to get some data to a certain target node;
- Is a receiver – some node has data for it;
- Can relay data – will take data from another node, and pass it closer to its target.

Findings – Gupta & Kumar

- Due to interference effects, most communication happens between nearest neighbours.
  - Typically at distances of order $1/\sqrt{n}$.

- $\sqrt{n}$ node-node hops for a given Source->Destination route.
  - So the vast majority of traffic through the network is relayed.
  - Throughput per S-D pair decreases as $1/\sqrt{n}$.
  - So tends to 0!

This paper – summary

- Take Gupta & Kumar's model, attempt to improve throughput by introducing *mobility;*
- Nodes move through the network with randomly distributed trajectories.
- First idea:
  - Channel strength varies with respect to *distance;*
  - So buffer packets, and hand-over when S-D pair is physically close;
  - Infeasible – probability that a given pair is close together is very low.
- Solution:
  - Split the packet stream to as many near nodes as possible;
  - Nodes act as *mobile* relays;
  - Hand packet off to the destination when close.

Their model

- As with Gupta & Kumar, model *n* nodes in a unit area.
- Sender-centric model: the source picks which node to transmit to.
- Transmission is conditional - for a transmission from node *i* to *j,* received power / (noise + sum (power (other nodes))) > threshold.

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

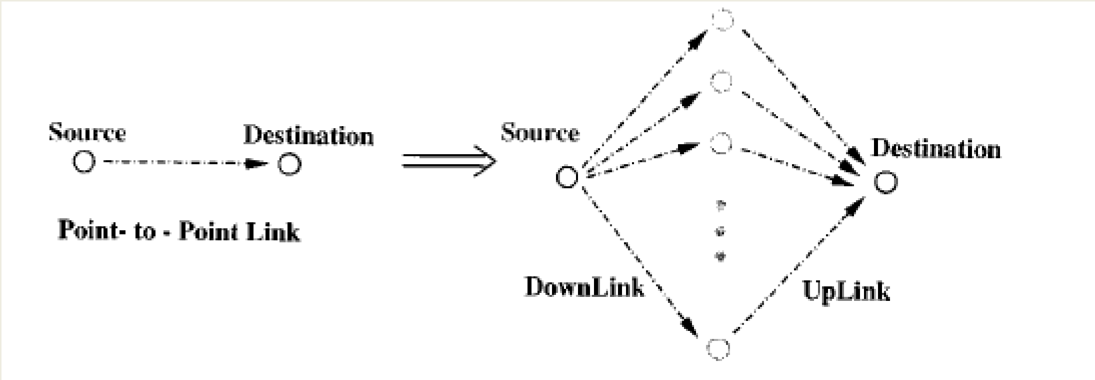
$$\liminf_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} M_i^{\pi}(t) \geq \lambda(n).$$

Bottom: throughput is random, and varies with trajectories. A long-term throughput of lambda is achievable if the total throughput across each S-D pair is >= lambda

Their model - assumptions

- Nodes transmit constantly;
- *Every* node is one source and one destination;
- Nodes move in randomly distributed trajectories.
- ...And can buffer infinitely!

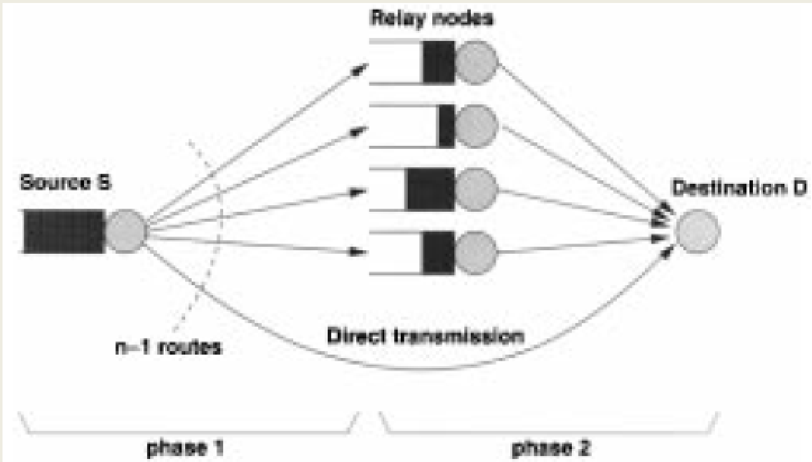
Impact of mobility



- If many nodes hold data, probability that at least one will move close to the destination is high.
- Since each S-D packet travels through at most 1 relay, the S-D throughput remains high (max 2 hops).
- $\Theta(1)$ Throughput!

Two-phase scheduling policy

- Scheduling policy π selects random S-D pairs for each timestep;
- Phase 1 – schedule transmissions from source to relay;
  - (Or from source to destination, if close);
- Phase 2 – schedule transmissions from relay to destination.



- Phases are interleaved at odd/even timesteps, respectively.

Proofs

Several pages of mathematical proofs, these show that:

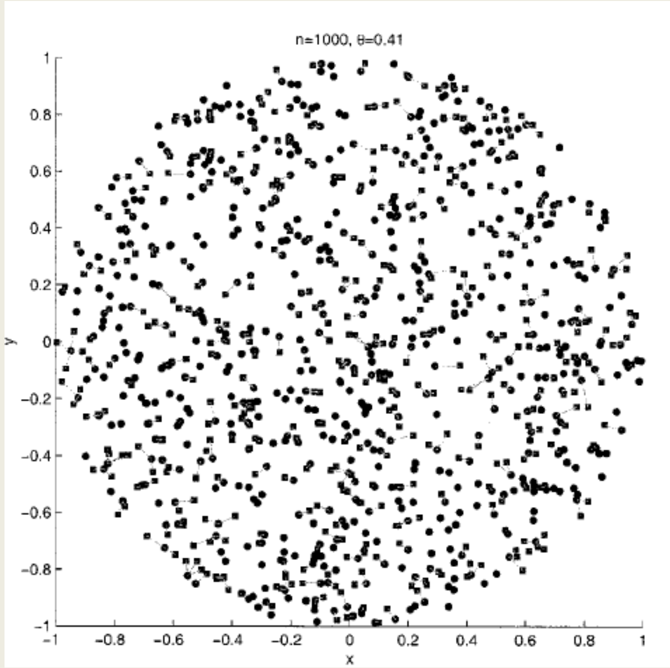
- Gupta & Kumar's model tops-out $O(1/\sqrt{n})$.
- Mobile nodes *without* relaying is infeasible:

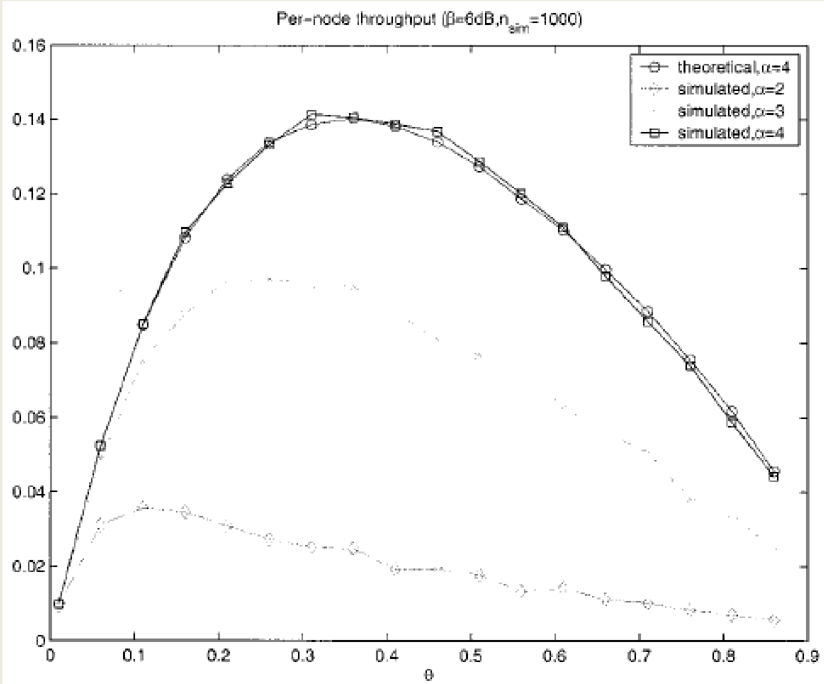
$$\sum_{i \in \mathcal{S}(t)} |X_i(t) - X_{j(i)}(t)|^\alpha \leq 2^\alpha \pi^{-\alpha/2} \frac{\beta + L}{\beta}.$$

- Mobile networks *with* relaying is effective!
  - And S-D throughput is constant, *independent* of *n* – $\Theta(1)$

Simulations

As well as providing proofs, they also simulated their model, comparing empirical results to theoretical predictions:





Close similarity between expected and actual throughputs.

Conclusions

- Mathematically proven constant throughput for ad-hoc networks of arbitrary size (given buffer/delay assumptions).
- Huge performance increase compared to previous fixed model.
- Targeted maximum throughput, so serious delays (hours) possible.
- Receiver-centric implementation yields higher throughput, but no proof.

Further work

- The model assumes random trajectories; this doesn’t seem particularly realistic:
  - What about nodes constrained to a certain area?
  - Or fixed trajectories?
  - Or clusters of nodes with related trajectories?

- Decreasing maximum throughput by relaying to >1 node should decrease delay. Investigate the trade-off for additional hops?

Thoughts & opinions

- Paper *very* theoretical – about 70% proofs!
- Overly complicated – simple concepts given complex explanations.
- Result is good, but very little discussion of their numerical investigation. Does the paper even need it?
- Some assumptions about 'delay-tolerance' are a bit dubious, as there are few applications for which delays of several hours would be an acceptable trade-off for added throughput.

Thank you!