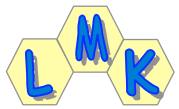
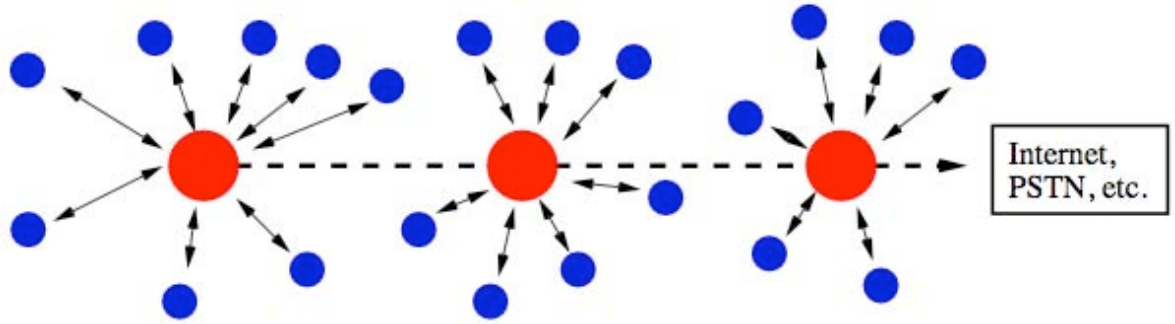
8. Wireless Ad-Hoc Networks

Literature:
S. Toumpis: Lecture Notes on Wireless Ad-Hoc Networks, Vienna University of Technology.
http://userver.ftw.at/~toumpis/courses/adhoc_2004/course.html

8.1 Overview
8.2 Capacity Scaling
8.3 Distributed Power Control
8.4 Topology Control
8.5 Routing
8.6 Medium Access Control

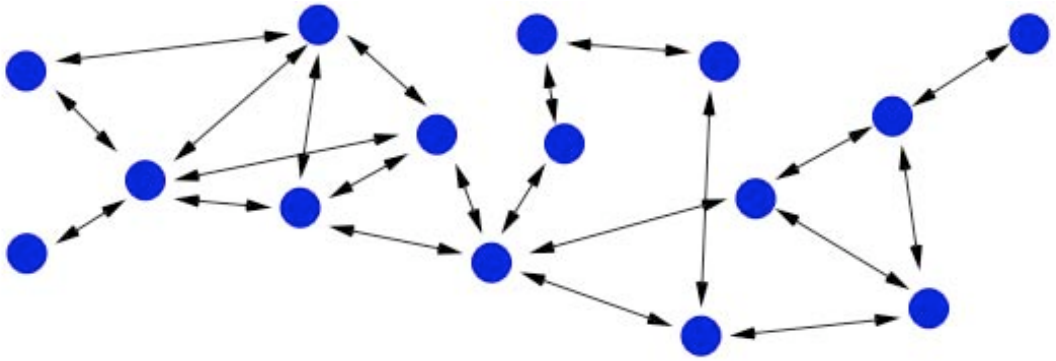


Cellular Topology



- Each node communicates only with closest base station.
- Base stations connected through high-capacity wires or optical fibers.
- Base stations do most of the work.
- Not a truly wireless network (only last hop is wireless) !

Ad-Hoc Topology



- No base stations, but nodes can talk to each other.
- Nodes have to get organized without the help of base stations. – *This is a much more challenging problem*!
- A truly wireless network!
- Another way to think about it: a wireless internet.

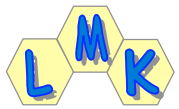
The Fundamental Challenge

There is no centralized network control, as in cellular networks.

All decision must be taken in a ***distributed*** manner. This greatly complicates the design of protocols!

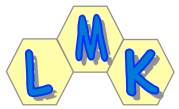
This implies the following sub-problems:

- How to handle collision due to interference?
- How to locate a destination?
- How to find a route to the destination?



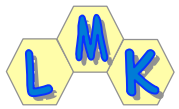
Why Ad-Hoc Networks?

- They can be build very fast. – No need to establish wired connections.
- They are very resilient. – No single point of failure, such as a base station.
- They are spectrally more efficient than cellular networks. – Every node can communicate with any other node, so nodes can make better use of the channel.
- Placing wires may be impossible, prohibitively expensive, or just not necessary.
- No need for operators.



Applications

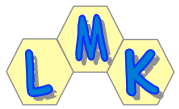
- Military communications (robustness and speed of deployment critical)
- Search and Rescue operations (same reasons)
- Sensor networks – For sensing forest fires, monitoring buildings, studying wildlife, etc.
- Networks in historical buildings where placing wires is not an option
- Wireless LANs in conferences, where placing wires would be a nuisance
- Networks of satellites (even around Mars!)
- Vehicular communications
- 4G wireless networks!



History

- Research started in the 70's. – ARPA Project initiated in December '72 at Stanford University meeting.
- Interest cooled off in the 80's.
- Renewed interest in the 90's, still going strong. – Wireless communications are very popular. – Today's powerful technology makes ad hoc networks practical.
- Different names for the same thing: – Packet radio networks (70's), multihop wireless networks (80's), wireless ad hoc networks (90's).
- UMTS contains an optional ad-hoc extension called ODMA (opportunity-driven multiple-access) which was pushed by Vodafone

Telenor: "The relay protocol ODMA (Opportunity Driven Multiple Access) has been analysed with regard to capacity, risk and regulatory aspects. Through theoretical studies and mathematical modelling, it has been demonstrated that ODMA has considerable ability to improve capacity utilisation in environments which are affected by signal deterioration. On the other hand, the technology is not mature, which leads to a significant degree of risk."



Important Problems

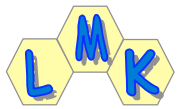
- Distributed Power Control
- Random Access
- Transmission Scheduling
- Topology Control
- Routing

8.2 Capacity Scaling

Consider a network with a very large number of nodes

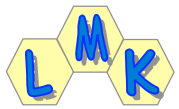
1. Fixed nodes
2. Mobile nodes
3. Throughput-delay trade-off

In cellular systems, capacity scales with the number of BS, but not with the number of subscribers.



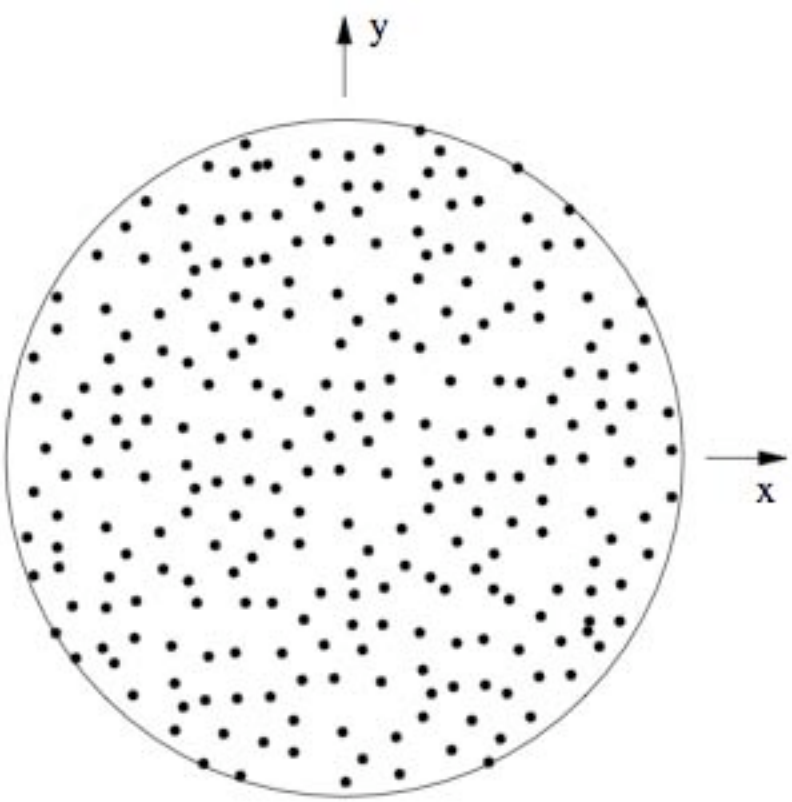
Methodology

- We study random network topologies.
- Therefore the capacity is a random quantity.
- So we only derive bounds on the capacity that hold with high probability (w.h.p.), i.e., with probability going to 1 as the number of nodes goes to infinity.
- Therefore, these bounds do not hold only for a given network realization, but for whole classes of networks.
- This approach also sheds light to the capabilities of networks with a modest number of nodes.



8.2.1 Fixed Nodes

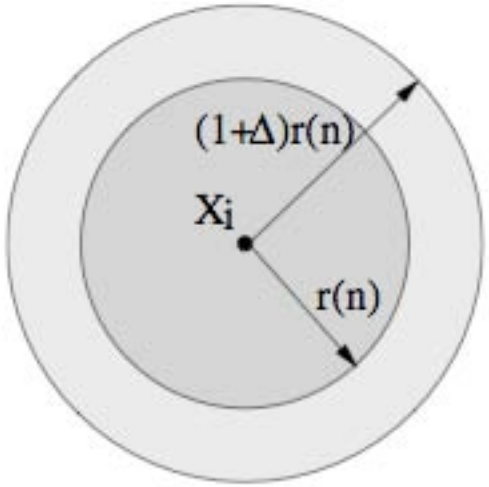
Network Model: Topology and Traffic



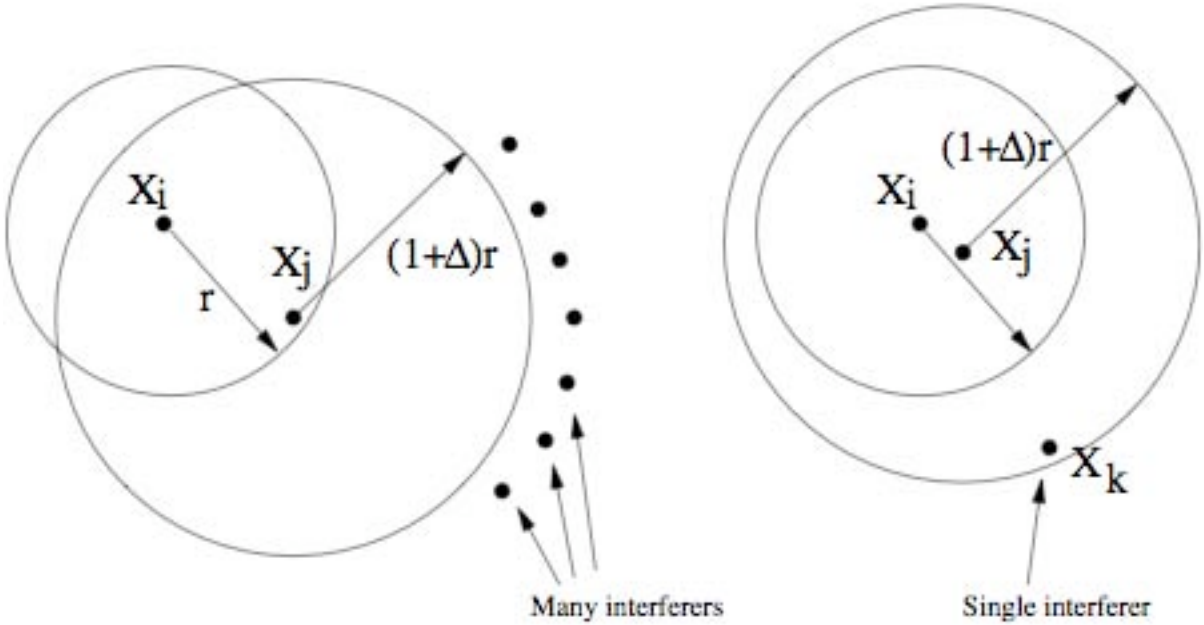
- n immobile nodes X_i, $i = 1, \ldots, n$, uniformly and independently placed in a disk of area $A = 1\ \mathrm{m}^2$.
- Each node has a **single** destination node, chosen randomly.
- All nodes require common end-to-end rate $\lambda(n)$.
- We define the **capacity** $C(n)$ as the maximum achievable $\lambda(n)$, multiplied by the number of nodes n.

Network Model: Interference Model

- A transmission from node X_i to node X_j is successful if and only if:
  - $|X_i - X_j| < r(n)$.
  - For all other simultaneously transmitting nodes X_k, $|X_k - X_j| > (1+\Delta)r(n)$.
- All transmissions are with rate W.
- Δ and $r(n)$ are the same for all nodes and $r(n)$ is a function of n.
- No interference mitigation.



Limitations of the Model



- According to the model, the transmission on the left is a success while that on the right leads to a collision.
- In reality, the opposite is more likely.

The Main Result

Theorem (Gupta & Kumar 2000):

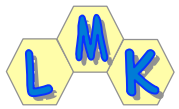
There are two constants K_1, K_2, such that

$$\lim_{n\to\infty} \Pr\left\{ K_1\sqrt{\frac{n}{\log n}} < C(n) < K_2\sqrt{\frac{n}{\log n}} \right\} = 1$$

Definition: A sequence of events E_n occurs with high probability (w.h.p.) iff $\lim_{n_\infty} \Pr(E_n) = 1.$

Therefore, the above theorem states that w.h.p.

$$K_1\sqrt{\frac{n}{\log n}} < C(n) < K_2\sqrt{\frac{n}{\log n}}$$



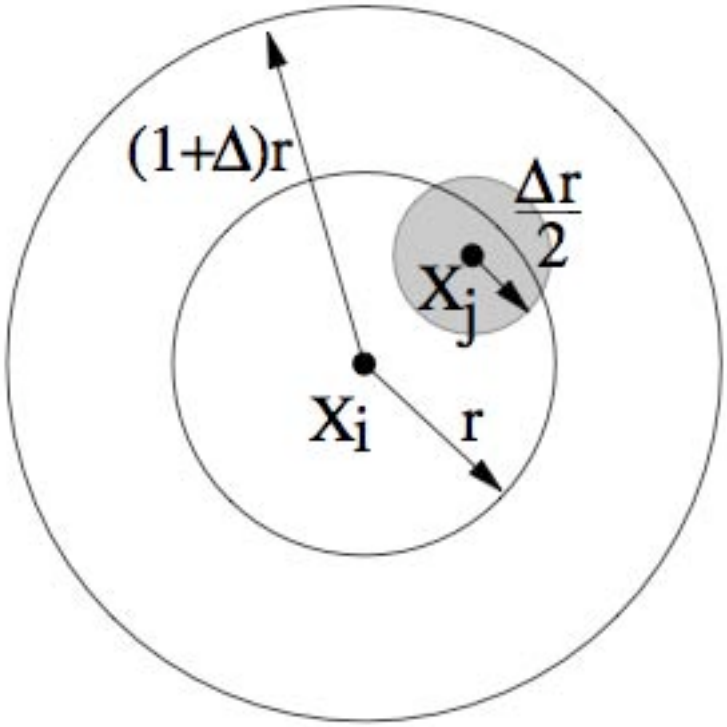
Remarks on the Result

- As the number of nodes $n \to \infty$, only the aggregate throughput will go to infinity. The per-node throughput will necessarily go to zero, roughly as $(n \log n)^{-1/2}$.
- Result is very good compared to cellular systems.
- With probability approaching 1, the capacity lies within a small interval.

The Upper Bound

$$\lim_{n\to\infty} \Pr\left\{ C(n) < K_2 \sqrt{\frac{n}{\log n}} \right\} = 1$$

The Optimum Length of a Hop



- Jammed area $A_J \sim r^2$ is proportional to square of length of a hop.
- Number of hops needed $M \sim 1/r$ is proportional to the reciprocal of the length of a hop.

Object function to minimize:

$$MA = r$$

Small hops are most efficient.

The Connectivity Constraint

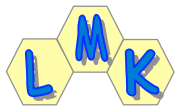
Problem: For arbitrary small hops, connectivity is lost!

From percolation theory, we have w.h.p.

$$r(n) > \sqrt{\frac{\log n}{n}}$$

This constraint bites if the neighborhood is unknown and random!
For nodes placed on a lattice, we get

$$r(n) > \frac{1}{\sqrt{n}}$$



The Upper Bound

The connectivity constraint bites:

$$r(n) > \sqrt{\frac{\log n}{n}}$$

Total throughput:

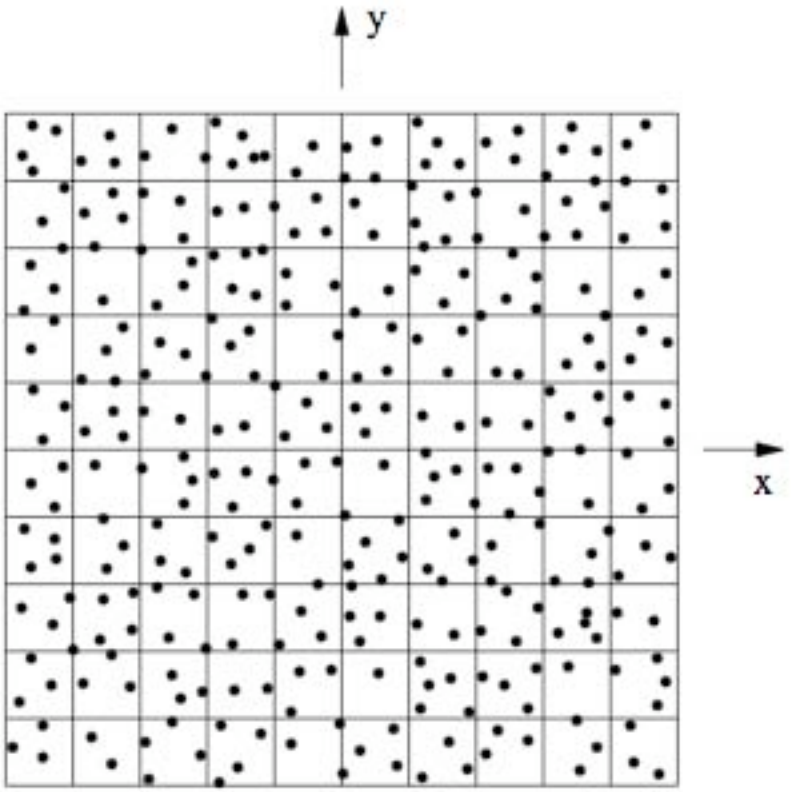
$$C(n) = K_2 \frac{A}{A_J} \frac{1}{M}$$

$$C(n) = K_2' \frac{A}{r^2(n)} r(n) < K_2 \sqrt{\frac{n}{\log n}}$$

The Lower Bound

$$\lim_{n\to\infty} \Pr\left\{ K_1 \sqrt{\frac{n}{\log n}} < C(n) \right\} = 1$$

Cell Lattice

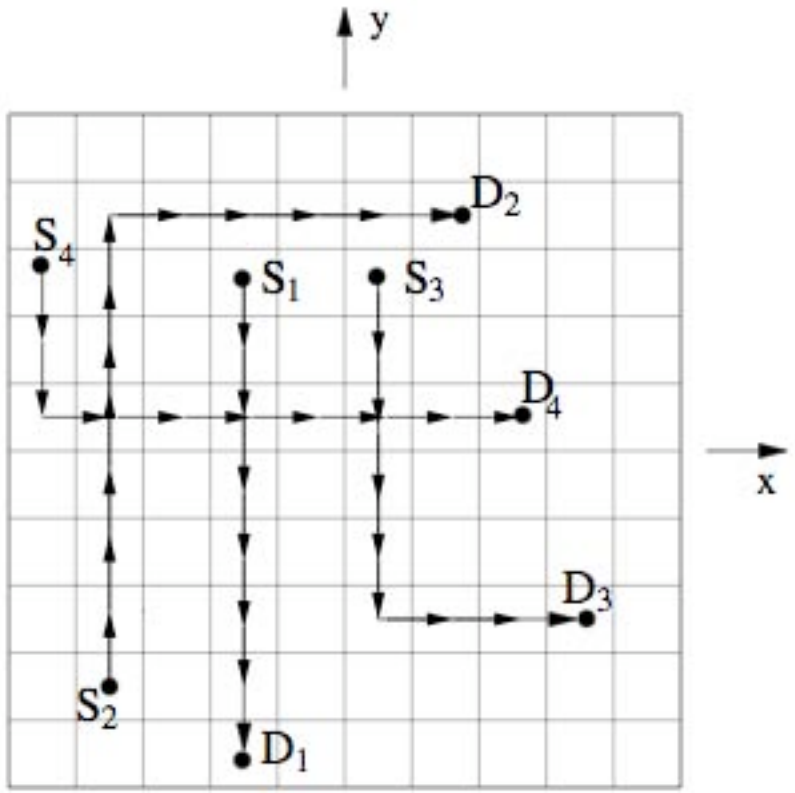


Rectangular grid simplifies the considerations.

Smallest cell width such that every cell contains at least one node:

$$r(n) > K_0 \sqrt{\frac{\log n}{n}}$$

The Routing Algorithm

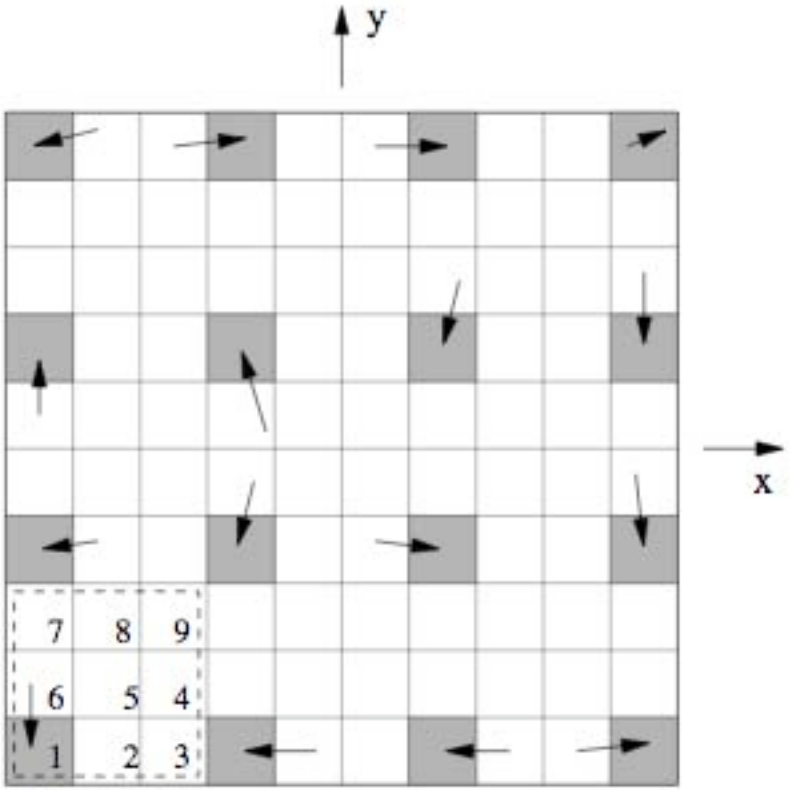


The number of hops is upper bounded by $M < 2/r(n)$.

Up to a factor of two, same as for upper bound!

How to meet the interference requirement?

Time Division Scheduling

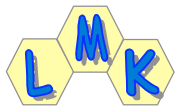


- In each time slot, 1 out of 9 sub-cells may receive.
- Minimum distances between receiving cells are maintained.

$$C(n) > \frac{A}{r^2(n)} \frac{2r(n)}{9} = K_1 \sqrt{\frac{n}{\log n}}$$

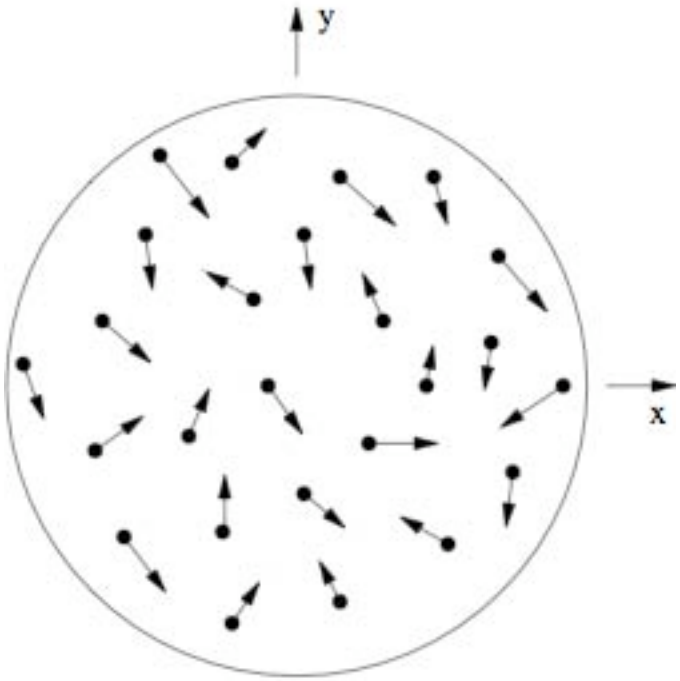
Extensions

- Fading: Lower bound is not reduced by more than a factor of $\log n$ for many fading models.
- 3-dimensional network: Under certain conditions capacity scales like $(n / \log n)^{2/3}$.
- Predefined locations of nodes: Similar bounds exist.
- Asymmetric traffic (much more destinations than sources):
  - Ratio smaller than $n^{1/2}$: No effect.
  - Ratio larger than $n^{1/2}$: Congestion around the sources.



8.2.2 Mobile Nodes

Mobility Model



Nodes move independently of each other, according to a stationary and ergodic random process: Brownian motion and random walk are both acceptable.

Each node has a random destination node (which is also moving).

Nodes create traffic with a common rate $_(n)$.

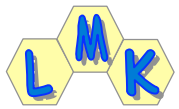
Two Hop Protocol

- Each node sends its message to its closest nodes.
- The closest node fills up his buffer with messages when it moves around by becoming closest node to other nodes.
- When it becomes closest node to a destination node which it has a packet for it delivers it.

The goal of the two hops is to fill the buffer of the relay node such that is collects more and more messages and thus with high probability has a message to deliver to a destination at almost any position it moves to.

In steady state (when the buffer is filled), the following throughput is reached:

$$C(n) = K_1 n$$



Expected Delay

While the throughput of the 2-hop protocol is excellent, the average delay is terrible:

$$\mathrm{E}(d) \propto n$$

8.2.3 Throughput-Delay Trade-Off

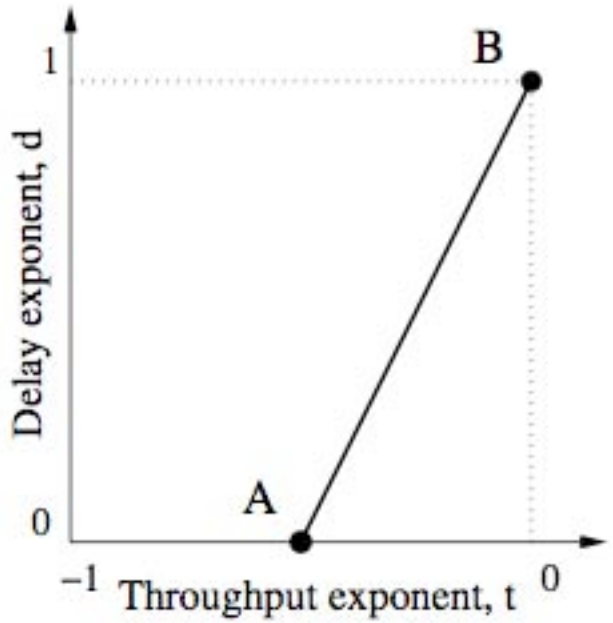
A Trade-Off of Exponents

Throughput exponent t:

$$\lambda(n) \propto n^t$$

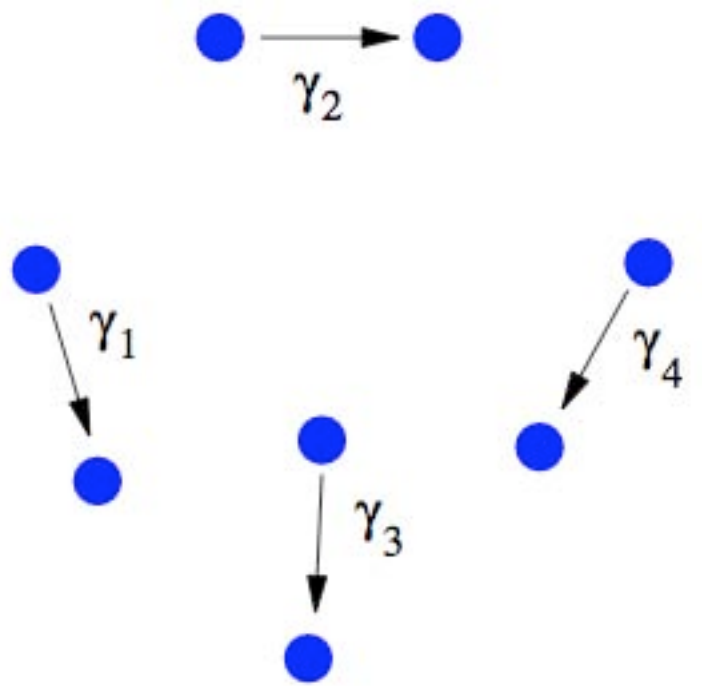
Delay exponent d:

$$d(n) \propto n^d$$



8.3 Distributed Power Control

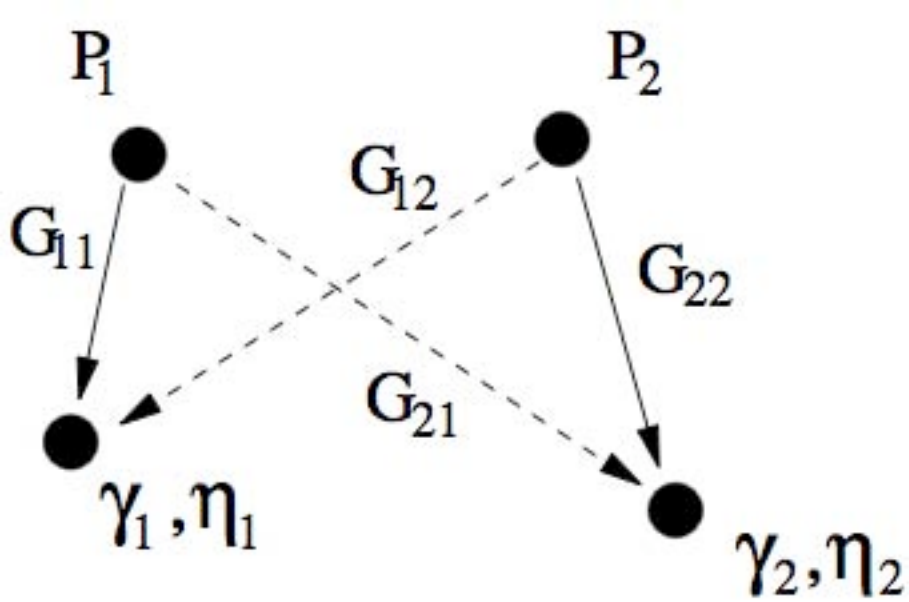
Power Control



- Nodes interfere with each other.
- Each node has a target SINR γ_i.
- Fundamental questions:
  - Are there powers P_i that achieve these γ_i?
  - Can they be found in a distributed manner?

Example

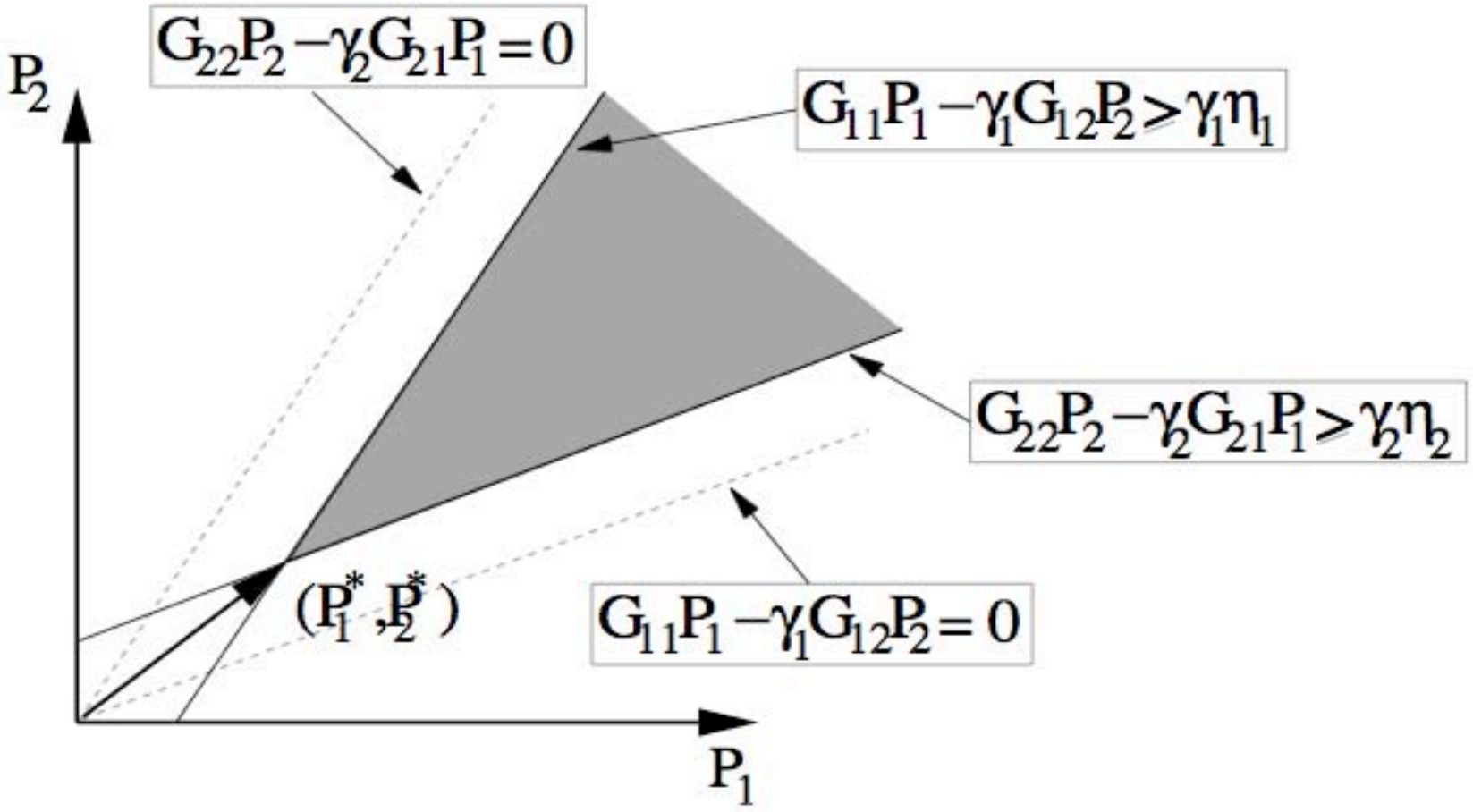
- Both nodes transmit with powers $P_i \in [0, \infty)$.
- Nodes are hampered by thermal noise _$_i$.
- Target Signal-to-interference-and-noise ratio is _$_i$.



$$\frac{G_{11}P_1}{\eta_1 + G_{12}P_2} \geq \gamma_1$$

$$\frac{G_{22}P_2}{\eta_2 + G_{21}P_1} \geq \gamma_2$$

Power Feasibility Region

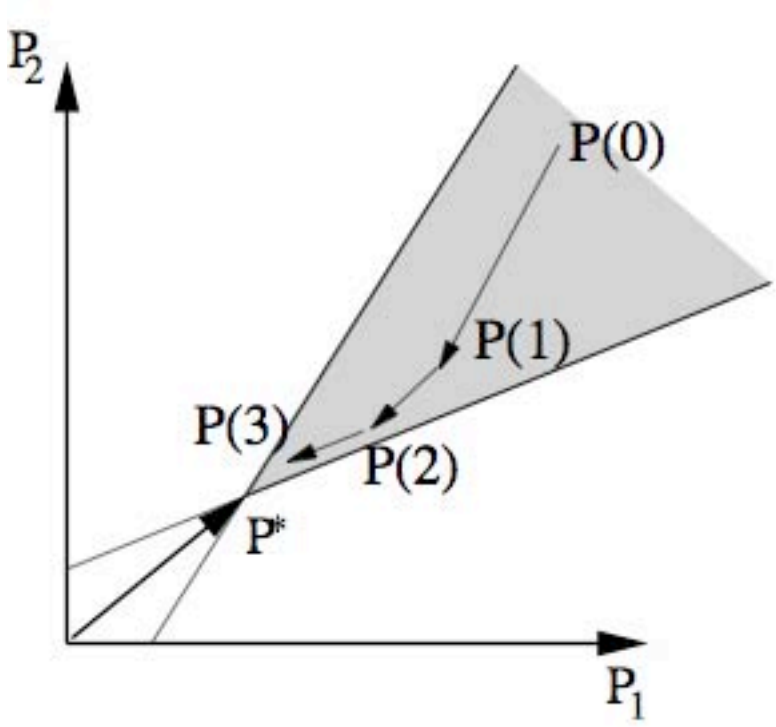


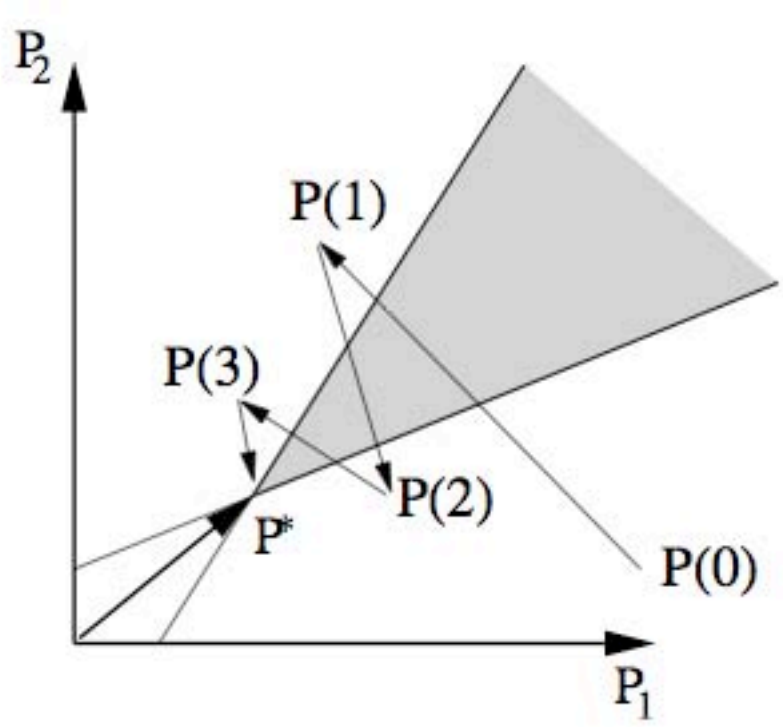
The point $P = (P_{-1}, P_{-2})$ is optimal, because it minimizes energy consumption.

A Distributed Algorithm

- We need distributed solution:
  - Each node uses only information it has locally: measured SINR and its own transmitter power.
  - Only distributed solutions scale with the number of nodes (very important in wireless ad hoc networks).
- One solution:
  - We slot time (and index slots by k).
  - Transmitter powers constant for the duration of a slot k: $P_i(k)$.
  - $P_i(k+1) = P_i(k) __i / \mathrm{SINR}_i(k)$.
  - Motivation: Each node tries to achieve SINR target in next slot, pretending the other node will keep their powers constant.
  - Very intuitive, but there is no reason why it should converge as $k _ \infty$.

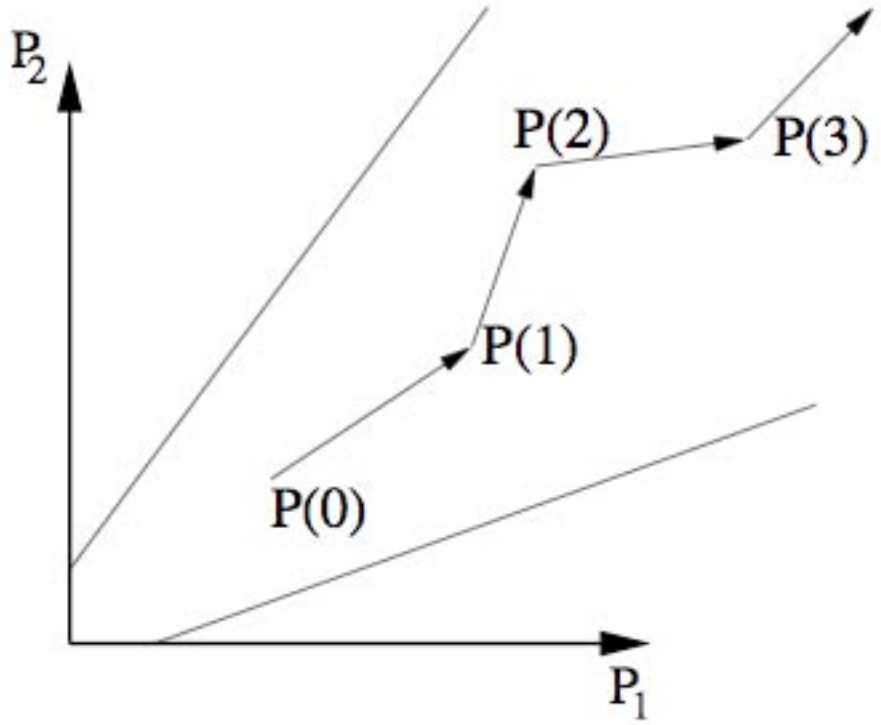
It Works!





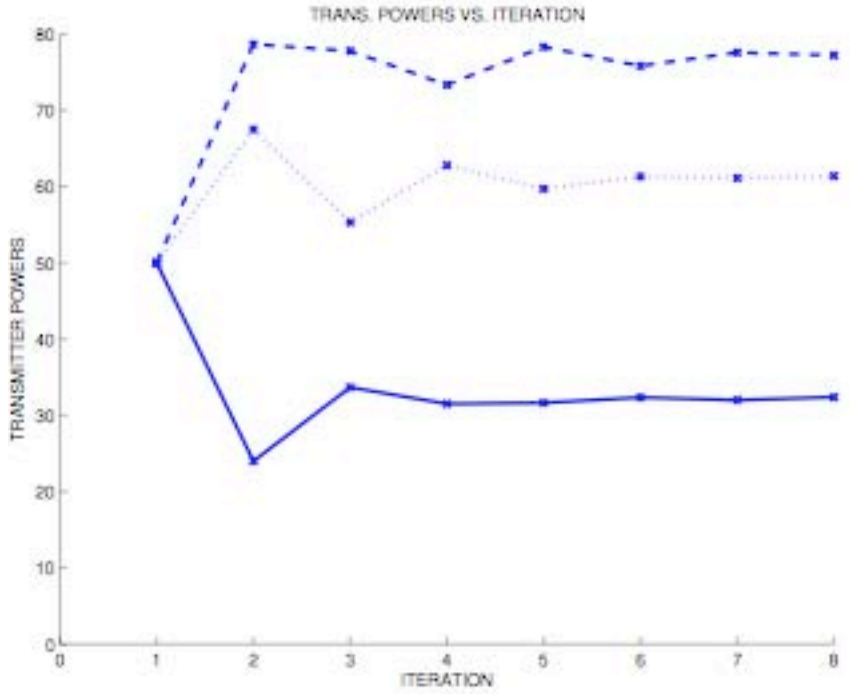
$$\lim_{k\to\infty} P(k) = P^*.$$

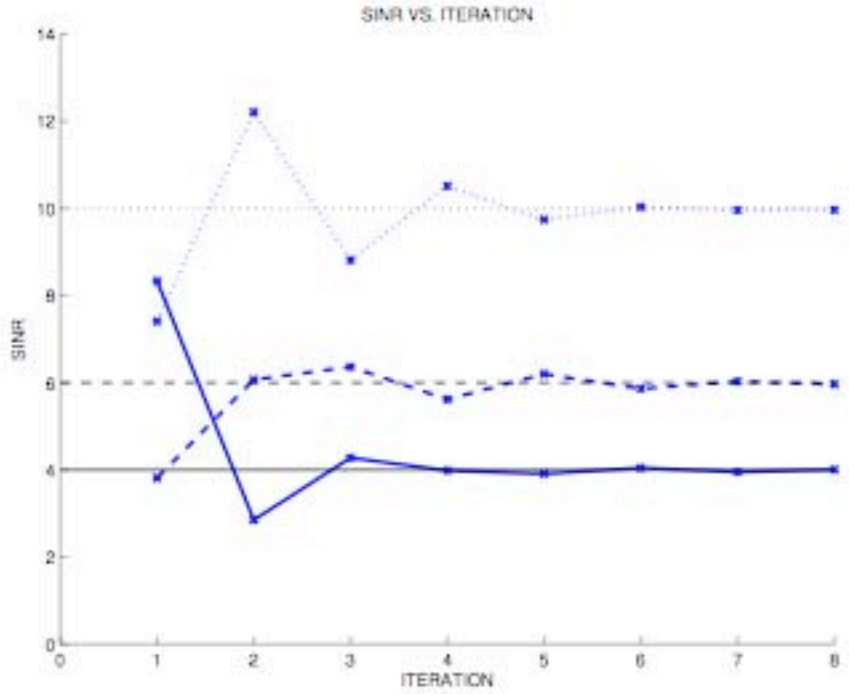
If a Solution Exists



$$\lim_{k \to \infty} P(k) = (\infty, \infty).$$

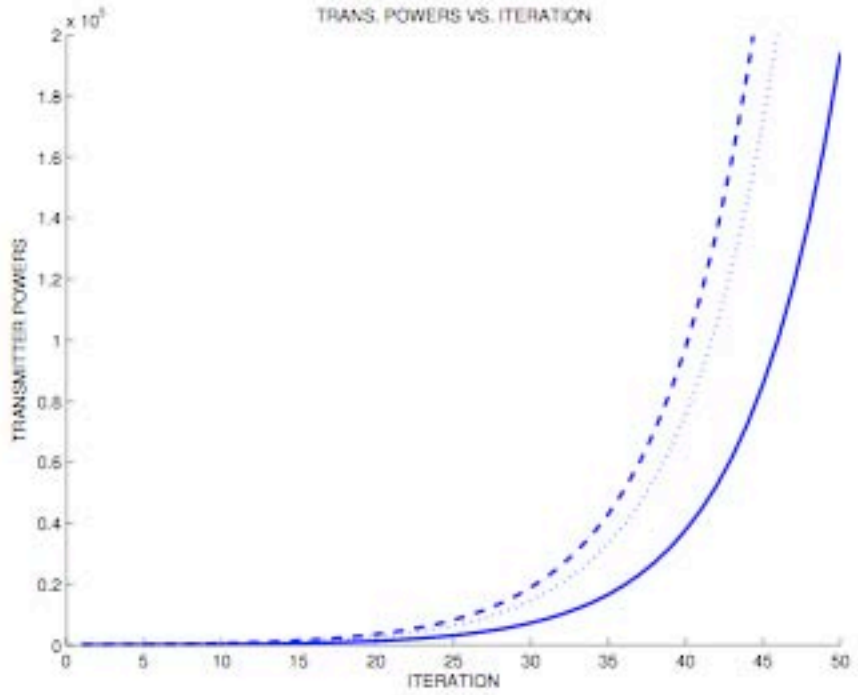
A Feasible Example

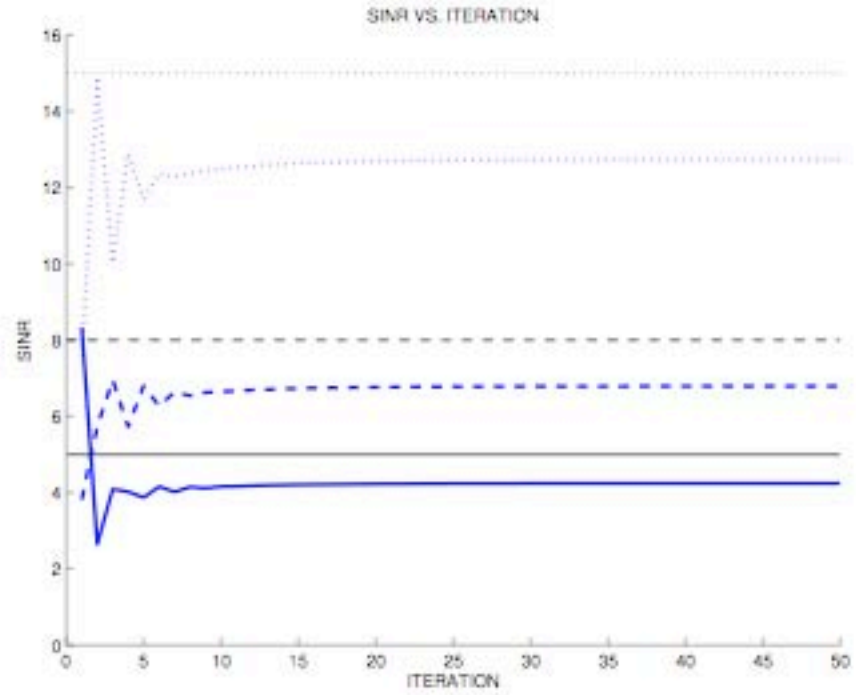




$$G = \begin{bmatrix} 1 & 0.06 & 0.04 \\ 0.09 & 0.9 & 0.126 \\ 0.064 & 0.024 & 0.8 \end{bmatrix}, \eta = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \gamma = \begin{bmatrix} 4 \\ 6 \\ 10 \end{bmatrix} \Rightarrow \rho_F = 0.8627, \mathbf{P}^* = \begin{bmatrix} 32.9882 \\ 79.0478 \\ 62.6049 \end{bmatrix}$$

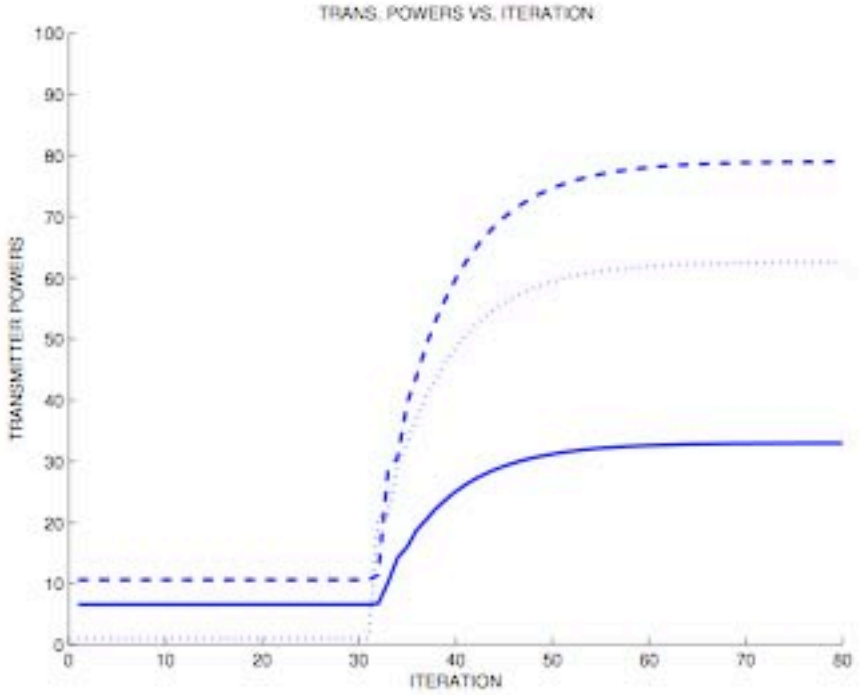
An Infeasible Example

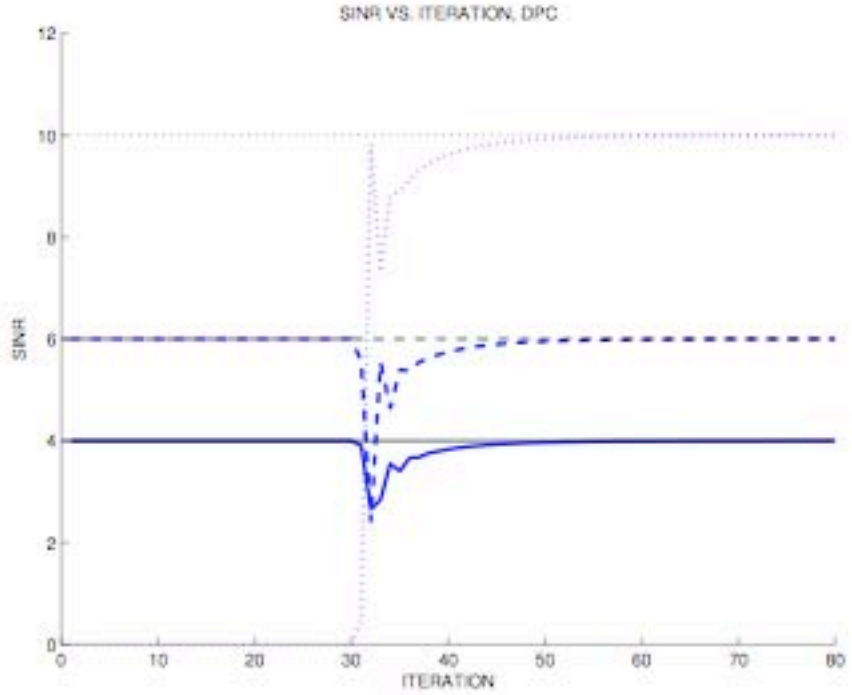




$$G = \begin{bmatrix} 1 & 0.06 & 0.04 \\ 0.09 & 0.9 & 0.126 \\ 0.064 & 0.024 & 0.8 \end{bmatrix}, \eta = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \gamma = \begin{bmatrix} 5 \\ 8 \\ 15 \end{bmatrix} \Rightarrow \rho_F = 1.1779$$

Example of Node Admission





$$G = \begin{bmatrix} 1 & 0.06 & 0.04 \\ 0.09 & 0.9 & 0.126 \\ 0.064 & 0.024 & 0.8 \end{bmatrix}, \eta = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \gamma = \begin{bmatrix} 4 \\ 6 \\ 10 \end{bmatrix}$$

$$\Rightarrow \rho_F^{2\ \text{USERS}} = 0.3795, \rho_F^{3\ \text{USERS}} = 0.8627.$$

Further Issues

- Node admission can make the problem infeasible and kill the existing links: Active link protection
- Fading can make the problem infeasible: Forced drop out

8.4 Topology Control

Motivation

The topology of a network changes due to

- reasons we can not control:

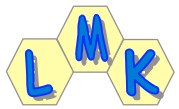
  node mobility, nodes malfunction, fading.

- reasons we can control:

  direction of antennas, transmitter power, etc.

How to respond to changes in topology?

- change routing.
- induce beneficial changes in topology: ***topology control.***



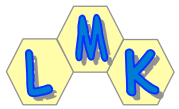
What is a Good Topology?

When is a topology bad?

If it is not connected, ...

When is a topology good?

If it is just connected, well connected, densely connected, fully connected?



Some Definitions

A network M is described as $M = (N, \mathbf{r})$ where N is a set of nodes, and $\mathbf{r}$ is a vector with their location.

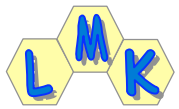
Each node u transmits with power $P(u)$. The power function $P(\cdot)$ is a design parameter.

For nodes u,v to be able to successfully communicate with each other, it is necessary that

$$P(u), P(v) \geq \lambda\left(\left\|r_u - r_v\right\|\right)$$

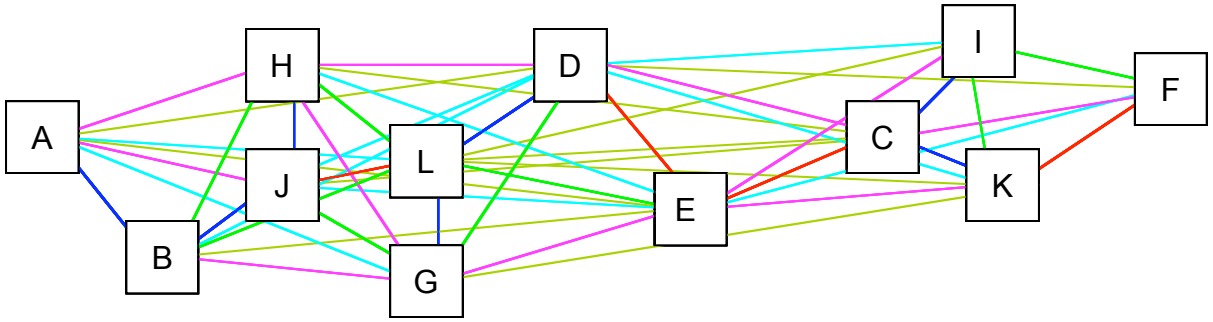
where the least-power function $\lambda(\cdot)$ is a monotonically increasing function.

A network M, a power function $P(\cdot)$ and a least-power function $\lambda(\cdot)$ define a graph $G\{M, P(\cdot), \lambda(\cdot)\}$.



Examples of Graphs

... for N = {A, B, . . . ,L}, the following position of nodes:



Good Graphs

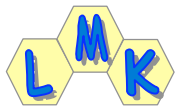
... must be connected, otherwise some nodes are not reachable.

... even if they are connected, they should not have bottlenecks.

... should not be too dense:

- Nodes would consume more power than needed.
- Spatial reuse would be hindered.

Without topology control, mobile networks will often loose connectivity or become too dense.



Connected Min-Max Power Problem

Task:

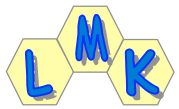
Given

- a static network M = (N, $\mathbf{r}$),
- a least-power function _(·),

Find an assignment of powers such that

- the induced graph G{M, _(·), $P(\cdot)$} is connected,
- $\max_{u \in \mathrm{N}} P(u)$ is minimum.

That means everyone can communicate with everyone else and everyone needs as little power as possible.



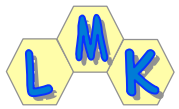
The CONNECT Algorithm

1. sort node-pairs in non-decreasing order of mutual distances
2. initialize |N| clusters, one per node
3. for each pair of nodes (u,v) in sorted order do:

   3.1 If $\text{cluster}(u) \neq \text{cluster}(v)$ then

      3.1.1 $P(u) = P(v) = \lambda(\square |r_u - r_v|)$

      3.1.2 merge $\text{cluster}(u)$ with $\text{cluster}(v)$
4. until the number of clusters is 1
5. minimize required power per node



Minimize Power per Node in Connected Graph

1. let S be the list of sorted node pairs
2. for each node u do

   2.1 define the set T = $\{(n_1,n_2) \in$ S : $u = n_1$ or $u = n_2\}$

   2.2 sort T in non-increasing order of distance

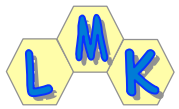
   2.3 discard from T all pairs (x,y) with $\lambda(|r_x - r_y|) > P(u)$

   2.4 for all remaining (=connected) pairs $(x,y) \in$ T

      2.4.1 set $P(u) = \lambda(|r_x - r_y|)$ if graph stays connected

Distributed Topology Control

- The CONNECT algorithm is centralized:
  - For mobile nodes, topology can have changed by the time the information has been gathered.
- We will consider a heuristic algorithms:
  - Local Information No Topology (LINT).
- Its protocol has zero-overhead:
  - It uses information that is available anyway, and does not require control packets.



Local Information No Topology (LINT)

Nodes have no global information about the topology.

- Let the degree of the node be the number of neighbors it has.
- Nodes try to keep their current degree d within some interval $[d_l, d_h]$.
- Ideally, d should be target degree d_t.
- If $d > d_h$, nodes power down.
- If $d < d_l$, they power up.
- Power up/down rule: $P_{new} = P_{old} _ (d_t/d)$–.

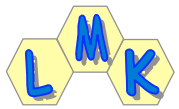
The power control rule is similar to distributed power control, except for the granularity of the degree.

Shortcomings of LINT

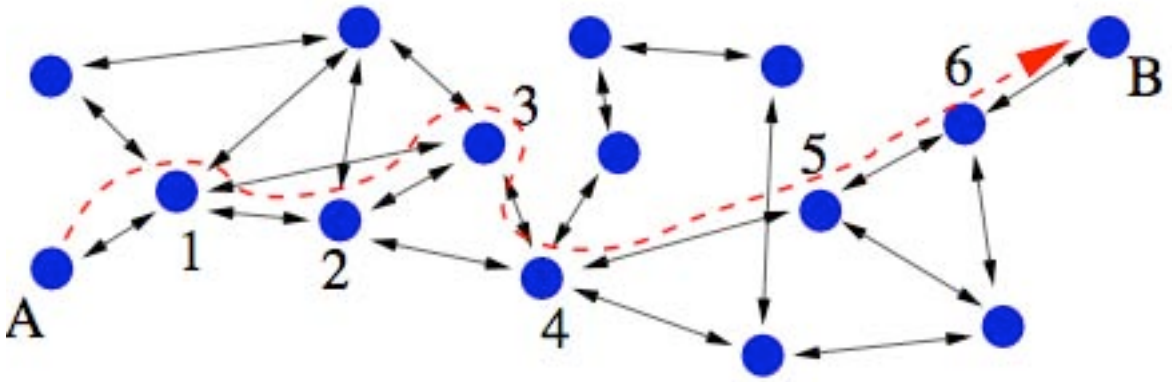
Basic tradeoff: As the target degree goes up, each node has more neighbors, and the topology is connected with higher probability, but the power consumption goes up.

The protocol works best when the placement of the nodes is random and uniform.

When nodes tends to cluster the network can brake into clusters.



8.5 Routing

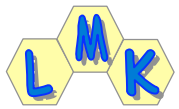


Nodes are not within the direct communication range of all other nodes.
Nodes need to discover routes (consisting of intermediate nodes) through which they can deliver their packets to their distant destinations.
This is the task of the routing protocol.
This task is complicated by the presence of node mobility.
The routing protocol must be coupled with a medium access control (MAC) protocol.
– The routing protocol specifies to whom a node should transmit the packet,
– The MAC protocol specifies when it should transmit the packet.

Route Discovery

A node that wants to send a packet to an unknown source,
broadcasts a ROUTE REQUEST packet.

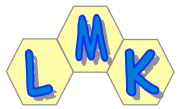
The neighbors reply
with a ROUTE REPLY packet if they know a route,
or broadcast another ROUTE REQUEST packet.



Route Maintenance

Once a link breaks, the nodes that use it to forward packets transmit back ROUTE ERROR packets to all potentially interested nodes.

Nodes go back to route discovery.



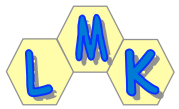
8.6 Medium Access Control

Nodes must decide when to access the channel, i.e., transmit.

- Two conflicting targets:
  - Collisions of packets must be avoided.
  - Bandwidth must not be underutilized.

- The MAC protocol must balance these targets.

- Classification:
  - Random Access
  - Transmission Scheduling
  - Hybrid methods (e.g. Reservation Aloha).



Carrier Sense Multiple Access (CSMA)

Nodes monitor the channel (i.e., there is channel sensing).

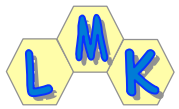
A node with a packet transmits only if it perceives an idle channel.

If a node with a packet perceives a busy channel, it waits for the channel to become available, then waits for a random time interval (to avoid collisions).

If there is a collision, the packet is backlogged for a random time interval.

Once a node starts to talk, it stops hearing.

In a totally connected network with zero propagation delays, CSMA is perfect.

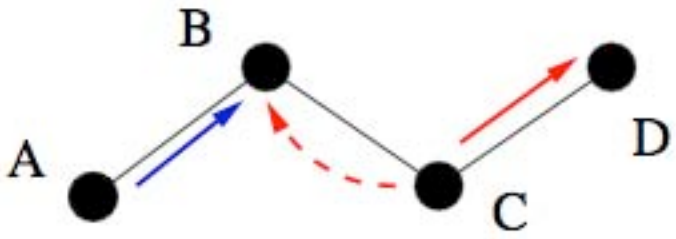


Problems of CSMA in Distributed Topologies

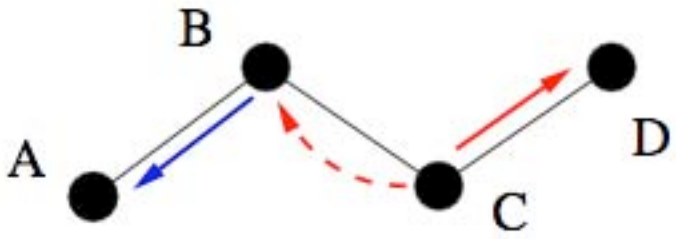
It is possible that a node senses the channel to be idle, but should not transmit (the hidden terminal problem).

It is possible that a node senses the channel to be busy, but should transmit (the exposed terminal problem).

1) Hidden Terminal Problem

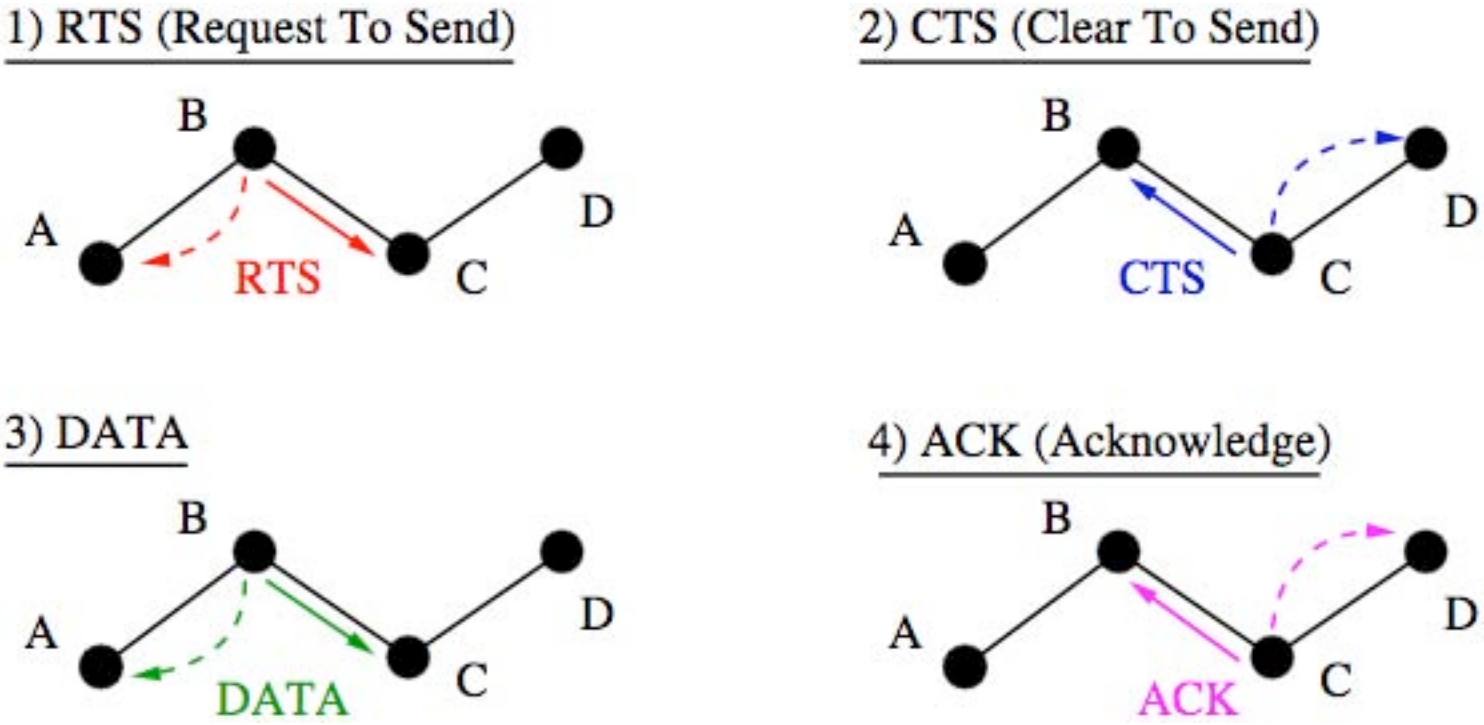


2) Exposed Terminal Problem



(In the examples, only nodes connected by a straight line can listen to each other's transmissions.)

CSMA with Collision Avoidance (CSMA/CA)



CSMA/CA is an improvement, but it is not perfect. For example, it introduces fairness issues, artificial restrictions on how close nodes may be placed, and so on.