Ad Hoc Wireless Networks : Analysis, Protocols, Architecture and Towards Convergence

P. R. Kumar

(with V. Borkar, P. Gupta, V. Kawadia, S. Narayanaswamy, R. Rozovsky, R. S. Sreenivas, L-L. Xie)

Dept. of Electrical and Computer Engineering, and
Coordinated Science Lab
University of Illinois, Urbana-Champaign

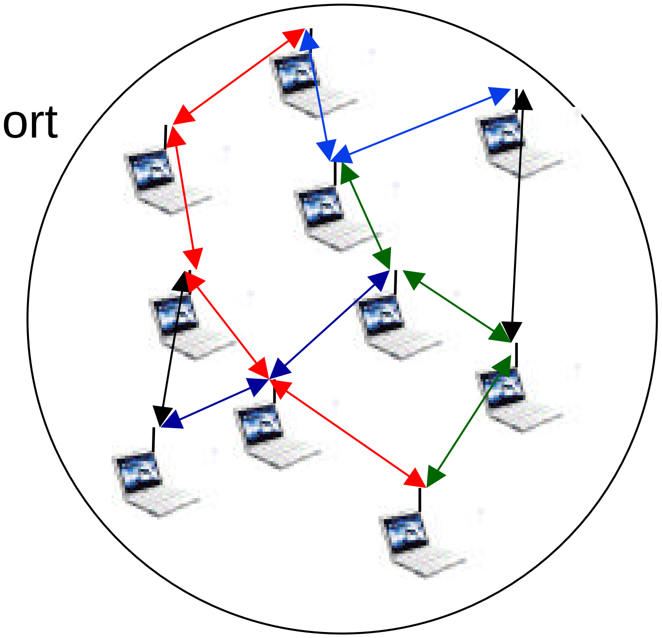
Phone 217-333-7476, 217-244-1653 (Fax)
Email prkumar@uiuc.edu
Web http://black.csl.uiuc.edu/~prkumar

Princeton/DIMACS, Oct 1, 2002

Wireless Networks

- Communication networks formed by nodes with radios

- Ad Hoc Networks
  - Current proposal for operation: Multi-hop transport
    - » Nodes relay packets until they reach their destinations
  - They should be spontaneously deployable anywhere
    - » On a campus
    - » On a network of automobiles on roads
    - » On a search and rescue mission
  - They should be able to adapt themselves to
    - » the number of nodes in the network
    - » the locations of the nodes
    - » the mobility of the nodes
    - » the traffic requirements of the nodes

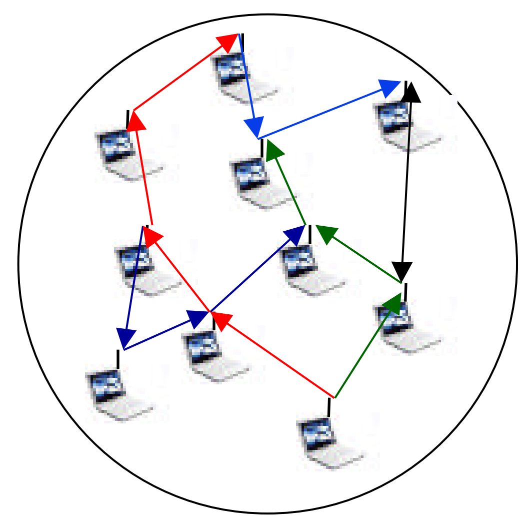


- Sensor webs

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport

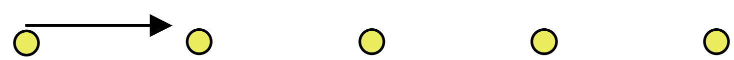
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of “wires in space”



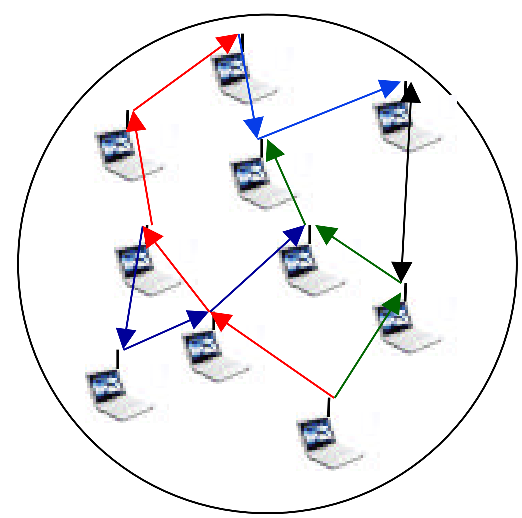
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



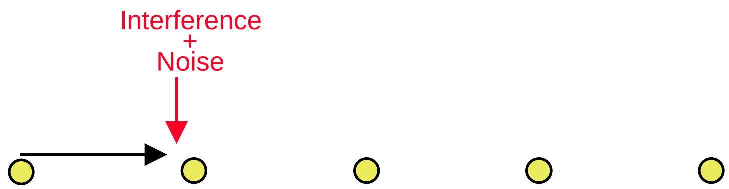
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of “wires in space”



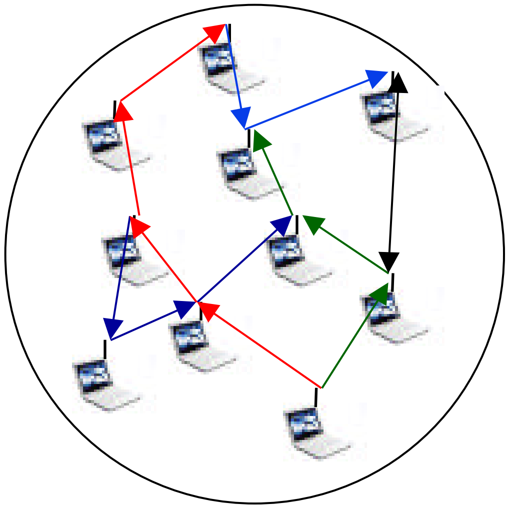
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- <u>Decode packet at each hop treating all interference as noise</u>
- Multi-hop transport



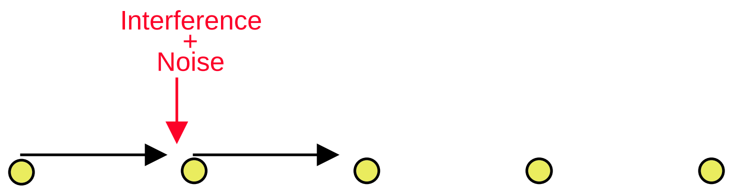
- Properties
  - <u>Simple receivers</u>
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of "wires in space"



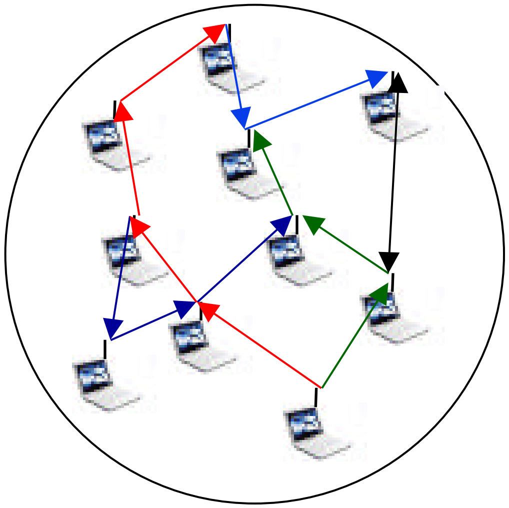
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



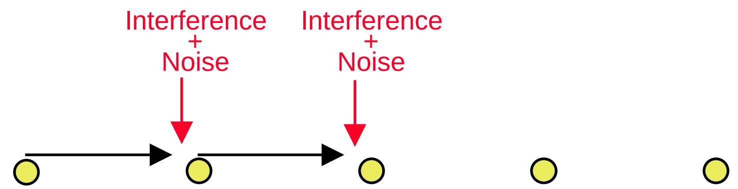
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of "wires in space"



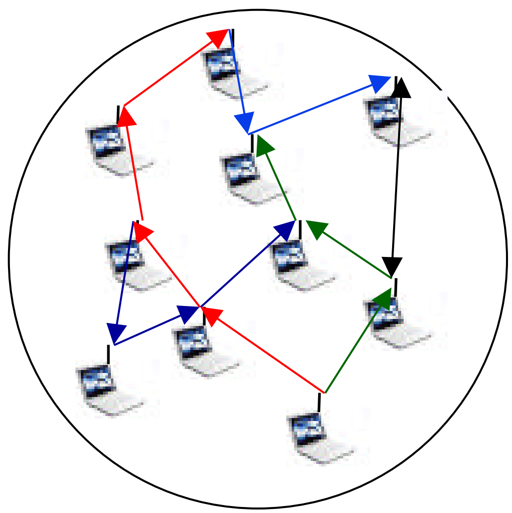
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



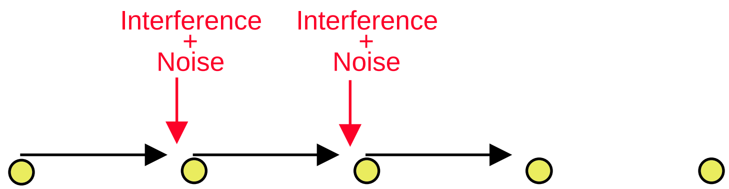
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of “wires in space”



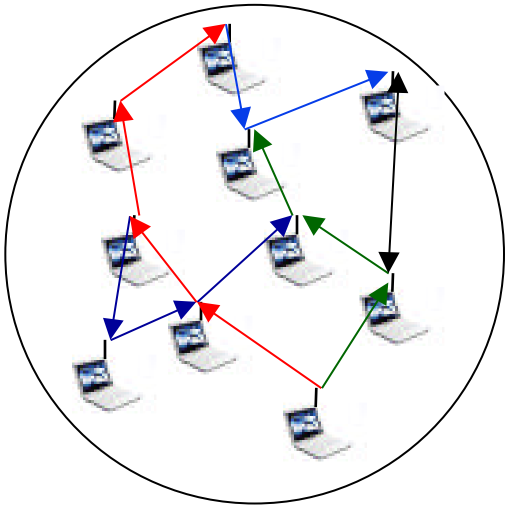
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- <u>Decode packet at each hop treating all interference as noise</u>
- Multi-hop transport



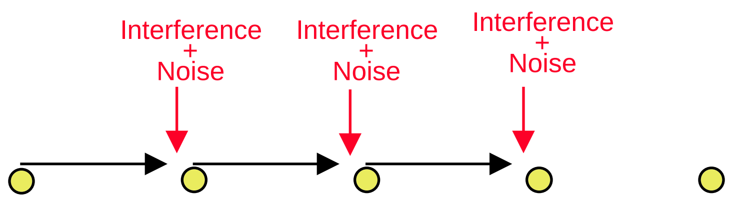
- Properties
  - <u>Simple receivers</u>
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of "wires in space"



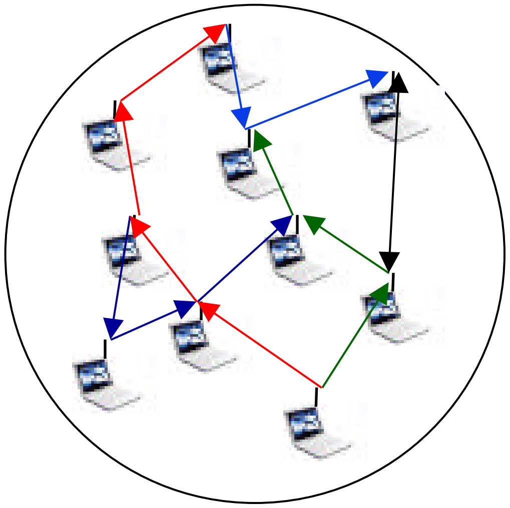
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



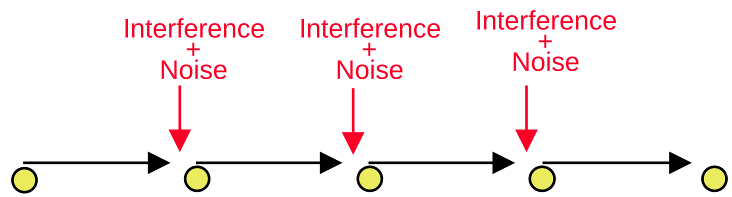
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of "wires in space"



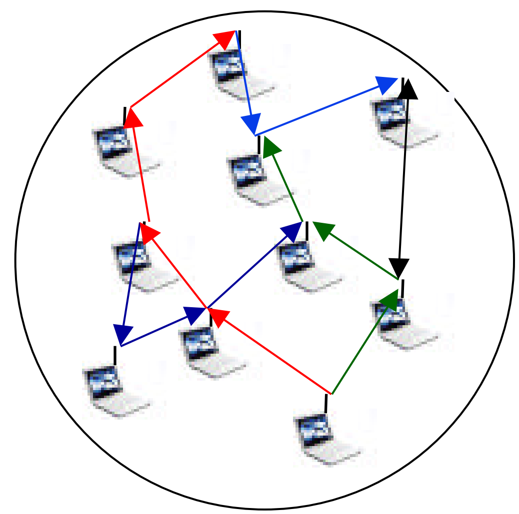
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



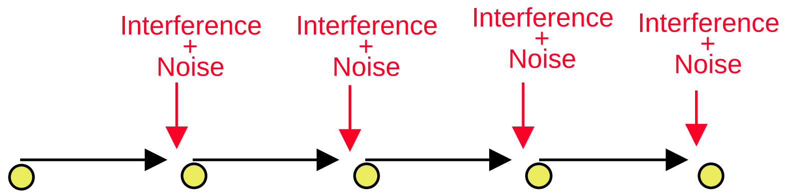
- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of "wires in space"



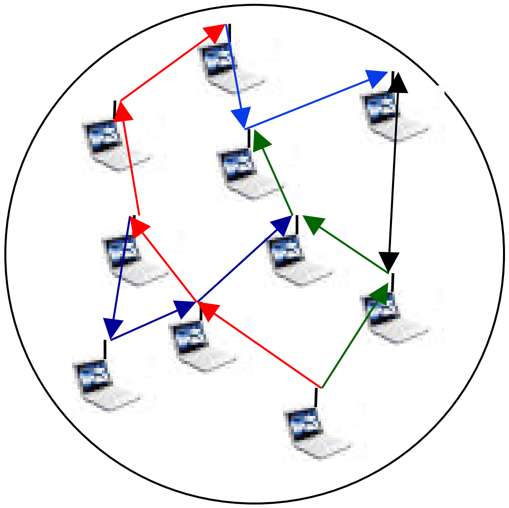
- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

Current proposal for ad hoc networks

- Decode packet at each hop treating all interference as noise
- Multi-hop transport



- Properties
  - Simple receivers
  - Simple multi-hop packet relaying scheme
  - Simple abstraction of “wires in space”



- This choice for the mode of operation gives rise to
  - Routing problem
  - Media access control problem
  - Power control problem
  - …..

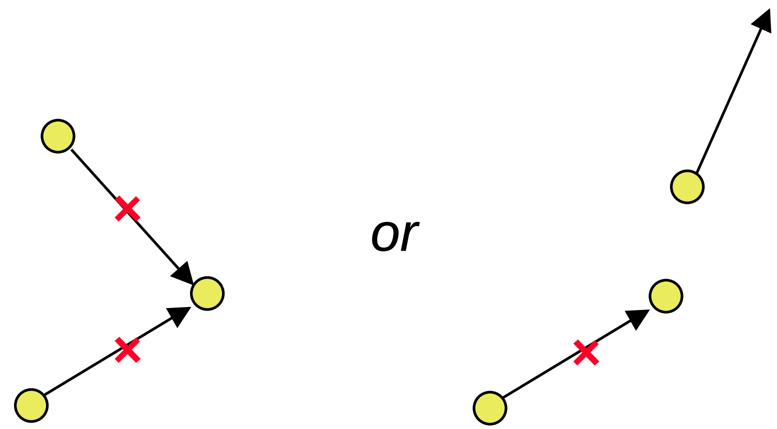
Three fundamental questions

- How much information can be transported over wireless networks if all interference is treated as noise?
- What is unconditionally the best mode of operation?
- What are the fundamental limits to information transfer in wireless networks?
  - How far is current technology from the optimal?
  - When can we quit trying to do better?
    - E.g.. If "Telephone modems are near the Shannon capacity" then we can stop trying to build better telephone modems
  - Once we determine the best strategy, then we can develop protocols for wireless networks

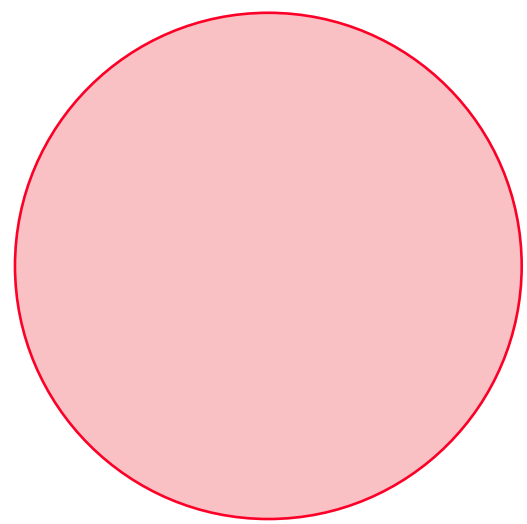
What is the maximum amount of information we can transport over wireless networks <u>if</u> all interference is treated as noise?

Suppose all interference is regarded as noise …

- Then packets can collide destructively



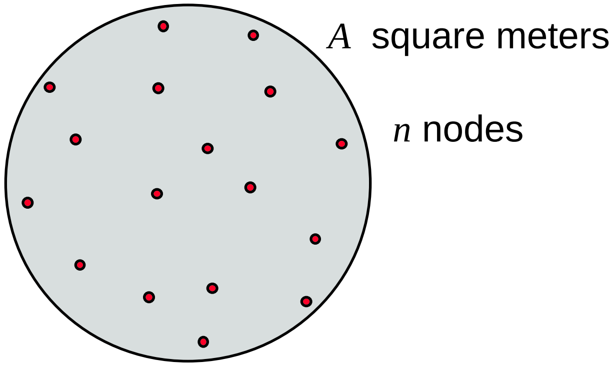
- <u>Model</u>
  - Reception is successful if
    - » Receiver not in vicinity of two transmissions



    - » Or SINR > β
    - » Or Rate depends on SINR

Scaling laws under interference model

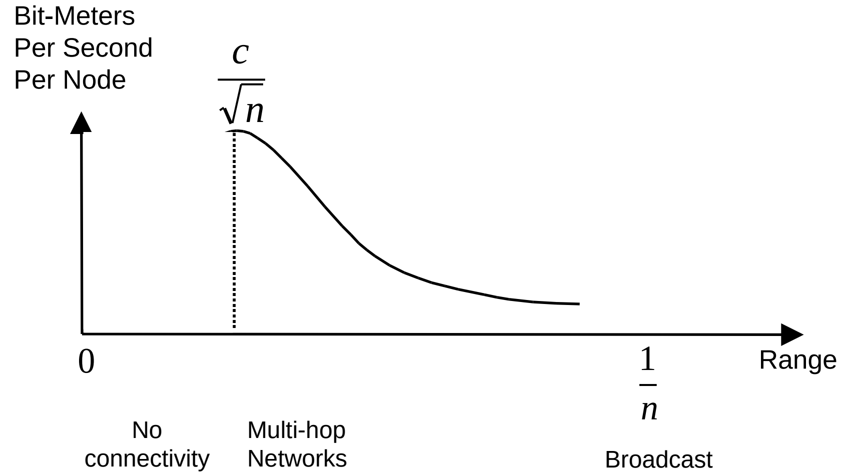
- <u>Theorems</u> (GK 2000)
  - Disk of area A square meters
  - n nodes
  - Each can transmit at W bits/sec



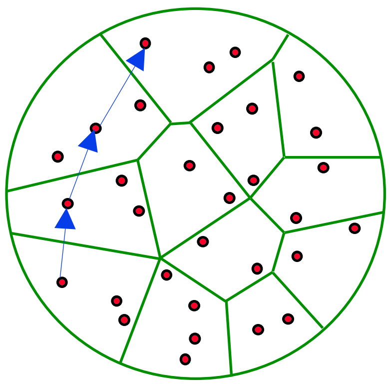
- <u>Best Case</u>: Network can transport $\Theta\left(W\sqrt{An}\right)$ bit-meters/second
  - <u>Square root law</u>
    - » Transport capacity doesn't increase linearly, but only like square-root
    - » Each node gets $\frac{c}{\sqrt{n}}$ bit-meters/second
- <u>Random case</u>: Each node can obtain a throughput $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$ bits/second

Optimal operation under “collision” model

- <u>Optimal operation is multi-hop</u>
  - Transport packets over many hops of distance $\frac{c}{\sqrt{n}}$



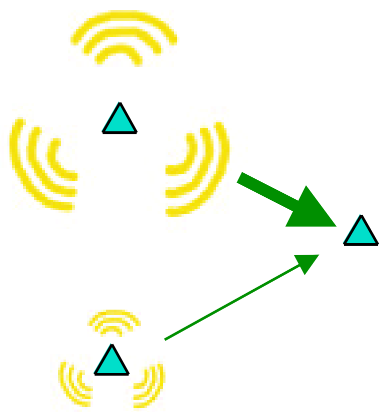
- <u>Optimal multi-hop architecture</u>
  - Group nodes into cells of size log n
  - Choose a common power level for all nodes
    - » Nearly optimal
  - Power should be just enough to guarantee network connectivity
    - » Sufficient to reach all points in neighboring cell
  - Route packets along nearly straight line path from cell to cell



But what are the fundamental limits to how much information can be transported over a wireless network?

Issue: Interference is not interference

- Excessive interference can be good for you
  - Receiver can first decode loud signal perfectly
  - Then subtract the loud signal
  - Then decode the soft signal perfectly
  - So excessive interference can be very good
  - Packets do <u>not</u> destructively collide



- Interference is information!

- So we need an <u>information theory</u> for networks to determine
  - How to operate wireless networks
  - How much information wireless networks can transport

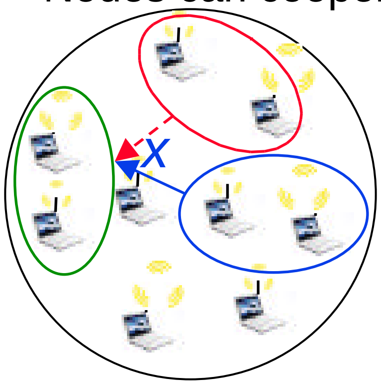
How should nodes cooperate?

- Wireless networks do not come with links
  - Nodes only radiate energy
  - Nodes can cooperate in complex ways

- Very complicated feedback strategies are possible
  - Notions such as “relaying,” broadcast,” may be too simplistic
  - The problem has all the complexities of team theory, partially observed systems,etc

How should nodes cooperate?

- Wireless networks do not come with links
  - Nodes only radiate energy
  - Nodes can cooperate in complex ways

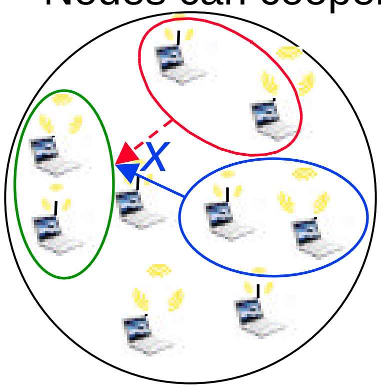


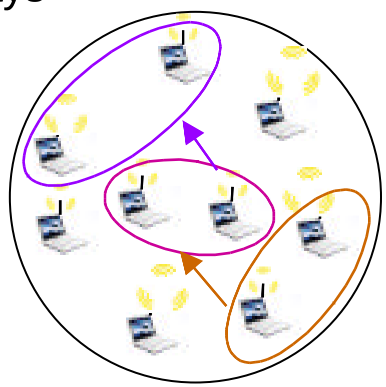
Nodes in Group A can help cancel the interference of nodes in Group B at nodes in Group C

- Very complicated feedback strategies are possible
  - Notions such as "relaying," broadcast," may be too simplistic
  - The problem has all the complexities of team theory, partially observed systems,etc

How should nodes cooperate?

- Wireless networks do not come with links
  - Nodes only radiate energy
  - Nodes can cooperate in complex ways





Nodes in Group A can help cancel the interference of nodes in Group B at nodes in Group C

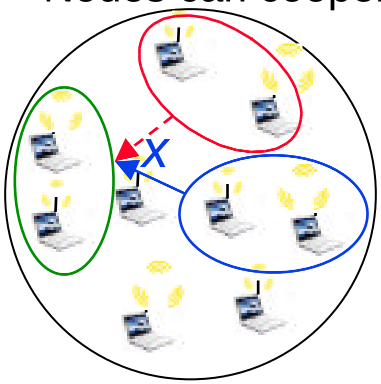
while

Nodes in Group D coherently transmit to relay packets from Group E to Group F

- Very complicated feedback strategies are possible
  - Notions such as “relaying,” broadcast,” may be too simplistic
  - The problem has all the complexities of team theory, partially observed systems,etc

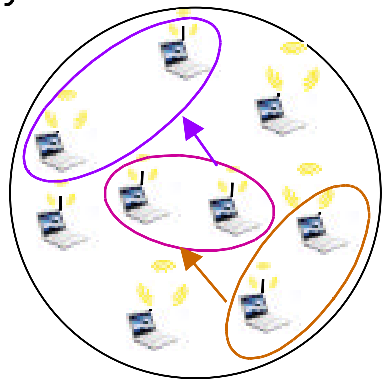
How should nodes cooperate?

- Wireless networks do not come with links
  - Nodes only radiate energy
  - Nodes can cooperate in complex ways



Nodes in Group A can help cancel the interference of nodes in Group B at nodes in Group C

while



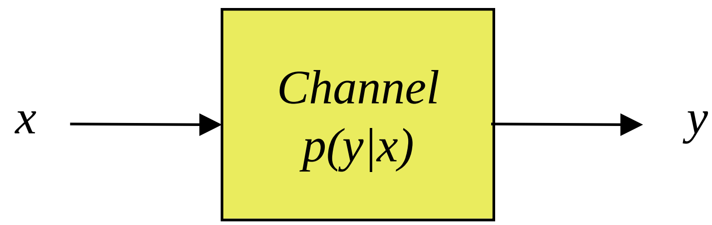
Nodes in Group D coherently transmit to relay packets from Group E to Group F

while … etc

- Very complicated feedback strategies are possible
  - Notions such as “relaying,” broadcast,” may be too simplistic
  - The problem has all the complexities of team theory, partially observed systems,etc

Shannon's Information Theory

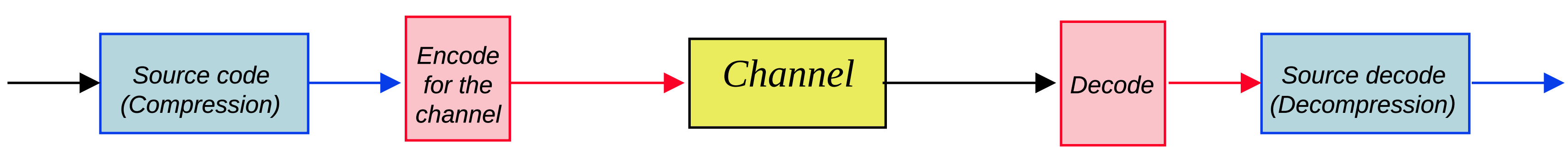
- <u>Shannon's Capacity Theorem</u>
  - Channel Model $p(y|x)$
    - » Discrete Memoryless Channel



  - <u>Capacity</u> = $\max\limits_{p(x)} I(X;Y)$ bits/channel use

$$I(X;Y) = \sum_{x,y} p(x,y) \log\left(\frac{p(X,Y)}{p(X)p(Y)}\right)$$

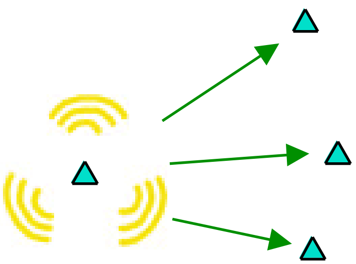
- <u>Shannon's architecture for digital communication</u>



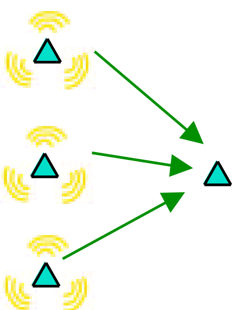
Network information theory

Triumphs	Unknowns

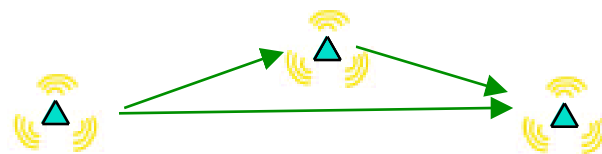
Gaussian broadcast channel



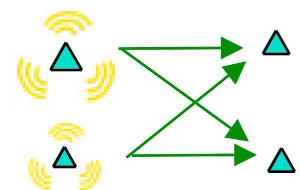
Gaussian multiple access channel



The simplest relay channel



The simplest interference channel

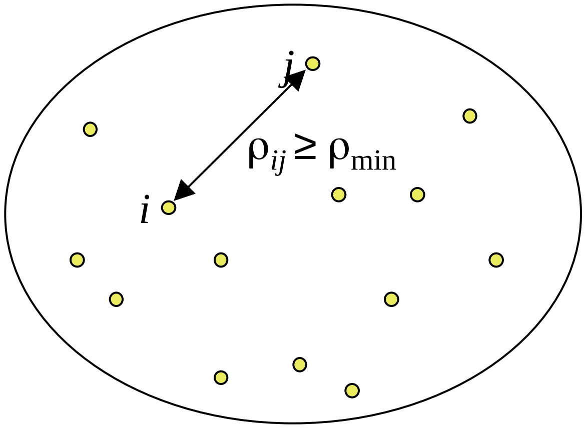


- Systems being built are much more complicated
  - Need a large scale information theory

The Model

Model of system: A planar network

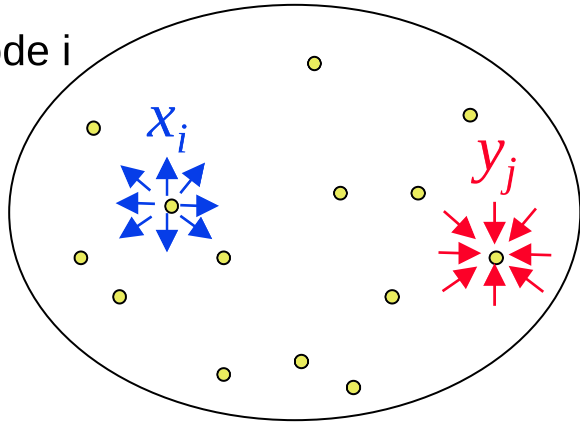
- n nodes in a plane
- ρ_{ij} = distance between nodes i and j
- Minimum distance ρ_{min} between nodes
- Signal attenuation with distance ρ: $\dfrac{e^{-\gamma\rho}}{\rho^{\delta}}$
  - $\gamma \geq 0$ is the <u>absorption constant</u>
    - » Generally $\gamma > 0$ since the medium is absorptive unless over a vacuum
    - » Corresponds to a loss of $20\gamma \log_{10} e$ db per meter
  - $\delta > 0$ is the <u>path loss exponent</u>



Transmitted and received signals

- W_i = symbol from some alphabet $\{1,2,3,\ldots,2^{TR_{ik}}\}$ to be sent by node i
- $x_i(t) = f_{i,t}(y_i^{t-1}, W_i)$ = signal transmitted by node i time t
- $y_j(t) = \sum_{\substack{i=1 \\ i \neq j}}^{n} \frac{e^{-\gamma \rho_{ij}}}{\rho_{ij}^{\delta}} x_i(t) + z_j(t)$ = signal received by node j at time t

  $z_j(t)$: $N(0,\sigma^2)$



- Destination j uses the decoder $\hat{W}_i = g_j(y_j^T, W_j)$
- Error if $\hat{W}_i \neq W_i$
- $(R_1, R_2, \ldots, R_l)$ is feasible rate vector if there is a sequence of codes with

$$\underset{W_1,W_2,\ldots,W_l}{Max} \Pr(\hat{W}_i \neq W_i \text{ for some } i \mid W_1, W_2, \ldots, W_l) \to 0 \text{ as } T \to \infty$$

- <u>Individual power constraint</u> $P_i \leq P_{ind}$ for all nodes i

  Or <u>Total power constraint</u> $\sum_{i=1}^{n} P_i \leq P_{total}$

The Transport Capacity: Definition

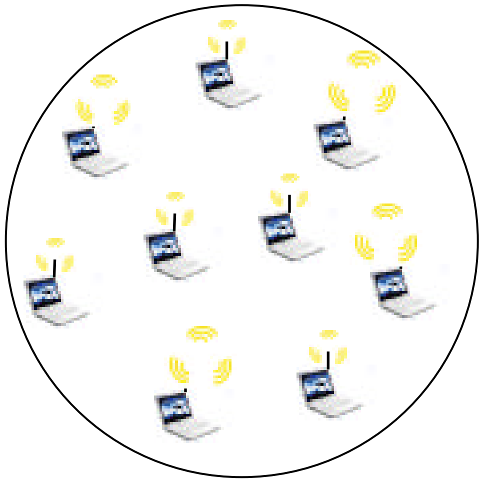
- Source-Destination pairs
  - $(s_1, d_1), (s_2, d_2), (s_3, d_3), \ldots, (s_{n(n-1)}, d_{n(n-1)})$
- Distances
  - $\rho_1, \rho_2, \rho_3, \ldots, \rho_{n(n-1)}$ distances between the sources and destinations
- Feasible Rates
  - $(R_1, R_2, R_3, \ldots, R_{n(n-1)})$ feasible rates for these source-destination pairs
- Distance-weighted sum of rates
  - $\Sigma_i R_i \rho_i$
- <u>Transport Capacity</u>
  - $C_T = \sup_{(R_1, R_2, \ldots, R_{n(n-1)})} \sum_{i=1}^{n(n-1)} R_i \rho_i$ bit-meters/second or bit-meters/slot

The Results

When there is absorption or a large path loss

The total power bounds the transport capacity

- Theorem (XK 2002)
  - Suppose $\gamma > 0$, there is some absorption,
  - Or $\delta > 3$, if there is no absorption at all
  - Then for all Planar Networks



$$C_T \leq \frac{c_1(\gamma, \delta, \rho_{\min})}{\sigma^2} P_{total}$$

where

$$c_1(\gamma, \delta, \rho_{\min}) = \frac{2^{2\delta+7}}{\gamma^2 \rho_{\min}^{2\delta+1}} \frac{e^{-\gamma\rho_{\min}/2}(2 - e^{-\gamma\rho_{\min}/2})}{(1 - e^{-\gamma\rho_{\min}/2})} \quad \text{if } \gamma > 0$$

$$= \frac{2^{2\delta+5}(3\delta - 8)}{(\delta - 2)^2(\delta - 3)\rho_{\min}^{2\delta-1}} \quad \text{if } \gamma = 0 \text{ and } \delta > 3$$

O(n) upper bound on Transport Capacity

- Theorem (XK 2002)
  - Suppose $\gamma > 0$, there is some absorption,
  - Or $\delta > 3$, if there is no absorption at all
  - Then for all Planar Networks

$$C_T \leq \frac{c_1(\gamma, \delta, \rho_{min}) P_{ind}}{\sigma^2} n$$

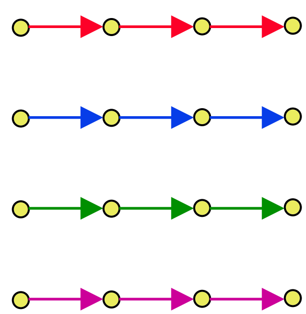
- Square root Law
  - Area = $\Omega(n)$
  - So $\Theta\left(\sqrt{An}\right) = \Theta(n)$

Optimality of multi-hop transport

- <u>Corollary</u>
  - So if $\gamma > 0$ or $\delta > 3$
  - And multi-hop achieves $\Theta(n)$
  - Then multi-hop is optimal with respect to the transport capacity

    - Up to order

- Example

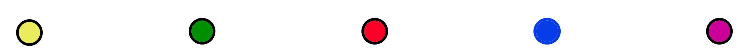


$\sqrt{n}$ sources each sending over a distance $\sqrt{n}$

What happens when the attenuation is very low?

Another strategy

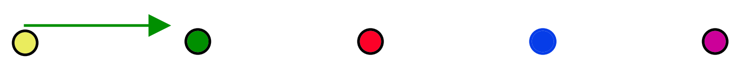
- Coherent multi-stage relaying with interference cancellation (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

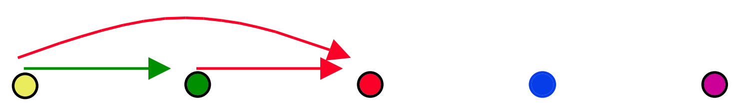
- Coherent multi-stage relaying with interference cancellation (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

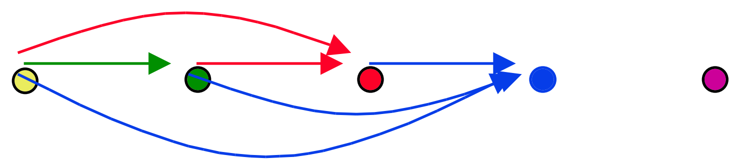
- <u>Coherent multi-stage relaying with interference cancellation</u> (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

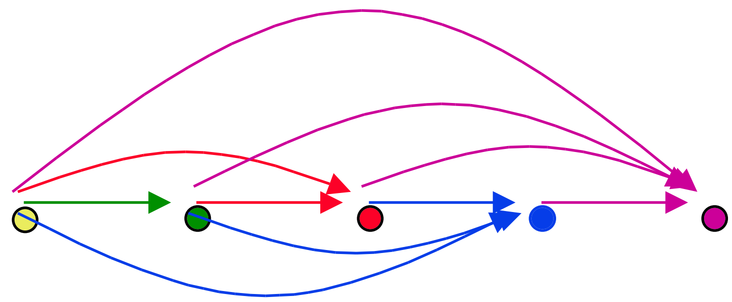
- <u>Coherent multi-stage relaying with interference cancellation</u> (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

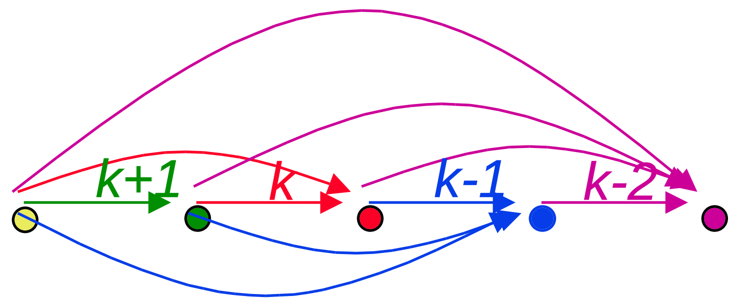
- Coherent multi-stage relaying with interference cancellation (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

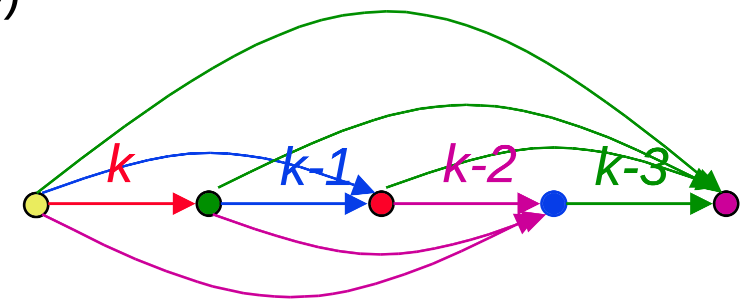
- <u>Coherent multi-stage relaying with interference cancellation</u> (COMSRIC)



- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

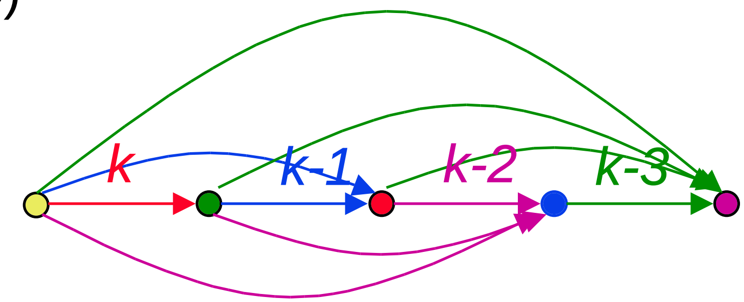
- Coherent multi-stage relaying with interference cancellation (COMSRIC)

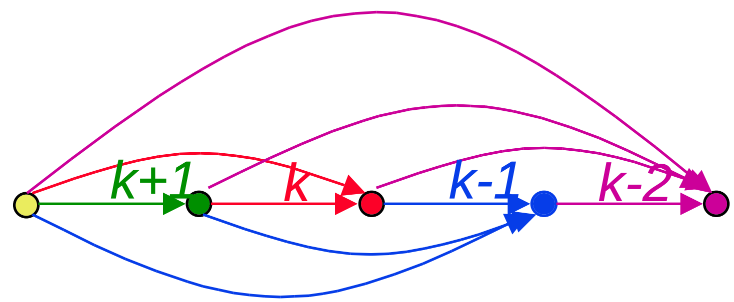


- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

- Coherent multi-stage relaying with interference cancellation (COMSRIC)

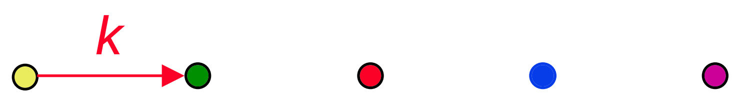


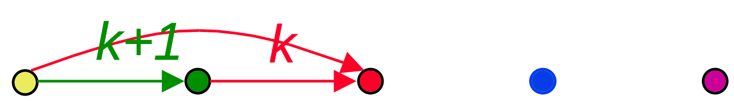


- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Another strategy

- Coherent multi-stage relaying with interference cancellation (COMSRIC)





- All upstream nodes coherently cooperate to send a packet to the next node
- A node cancels all the interference caused by all transmissions to its downstream nodes

Unbounded transport capacity can be obtained for fixed total power

- Theorem (XK 2002)
  - Suppose $\gamma = 0$, there is no absorption at all,
  - And $\delta < 3/2$
  - Then C_T can be unbounded in regular planar networks even for fixed P_{total}

Networks with transport capacity $\Theta(n^\theta)$

- <u>Theorem (XK 2002)</u>
  - Suppose $\gamma = 0$
  - For every $1/2 < \delta < 1$, and $1 < \theta < 1/\delta$
  - There is a family of linear networks with superlinear scaling law

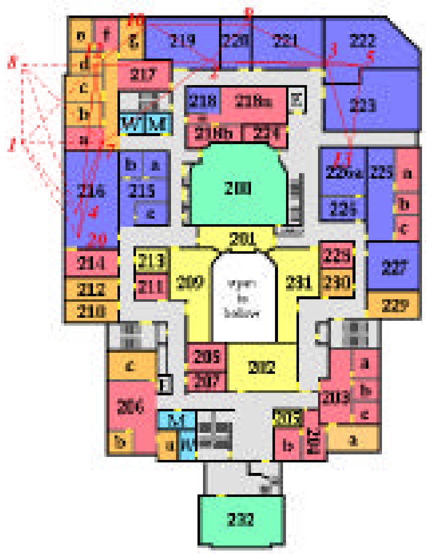
    $C_T = \Theta(n^\theta)$
  - The optimal strategy is coherent multi-stage relaying with interference cancellation

Some comments before we proceed to protocols ...

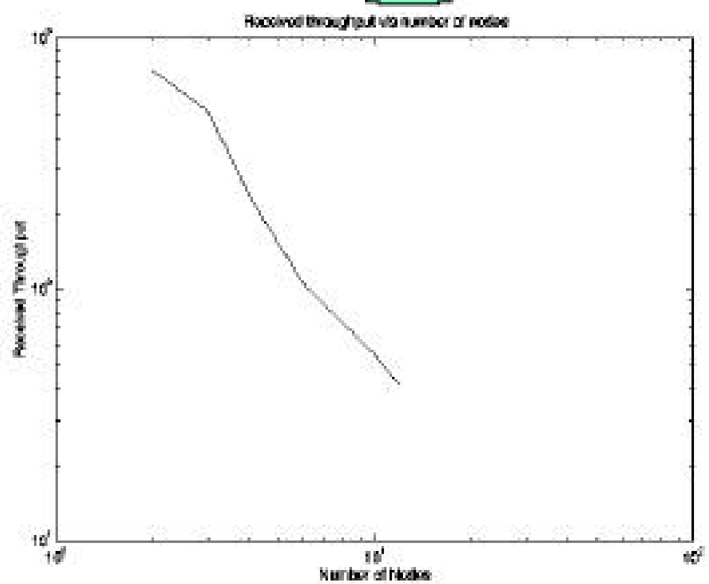
- Studied networks with arbitrary numbers of nodes
  - Explicitly incorporated distance in model
    - » Distances between nodes
    - » Attenuation as a function of distance
    - » Distance is also used to measure transport capacity
- Make progress by asking for less
  - Instead of studying capacity region, study the transport capacity
  - Instead of asking for exact results, study the scaling laws
    - » The exponent is more important
    - » The preconstant is also important but is secondary - so bound it
  - Draw some broad conclusions
    - » Optimality of multi-hop when absorption or large path loss
    - » Optimality of coherent multi-stage relaying with interference cancellation when no absorption and very low path loss
- Open problems abound
  - What happens for intermediate path loss when there is no absorption
  - The channel model is simplistic
  - ...

An experimental result

Experimental scaling law



Log(Thpt)



Log(Number of Nodes)

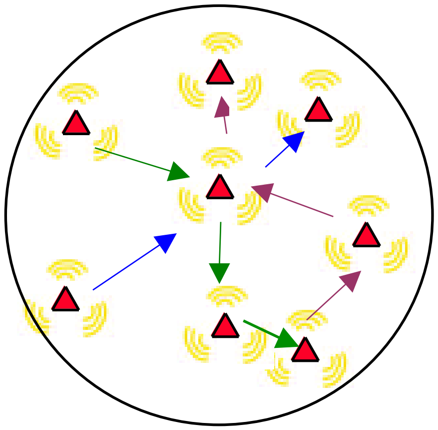
- Throughput = $2.6/n^{1.68}$ Mbps per node
  - No mobility
  - No routing protocol overhead
    - Routing tables hardwired
  - No TCP overhead
    - UDP
  - IEEE 802.11
- Why $1/n^{1.68}$?
  - Much worse than optimal capacity = $c/n^{1/2}$
  - Worse even than $1/n$ timesharing
  - Perhaps overhead of MAC layer?

Protocol design for wireless networks

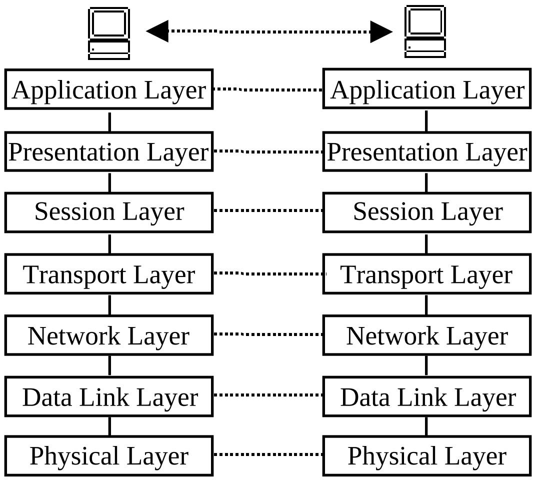
Protocol Design: The COMPOW Protocol for Power control (NKSK 2000)

The Power Control problem

- How do we choose power levels of transmissions in wireless networks?
  - Power level influences range
  - Power levels determine interference
  - Power levels affect routes



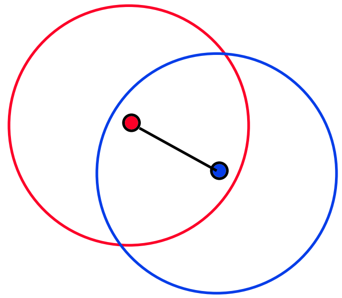
- Conceptualization problem for Power Control
- Which Layer?
  - Physical layer
    - » Quality of reception
  - Network layer
    - » Impact on routing
  - Transport layer
    - » Higher power impacts congestion



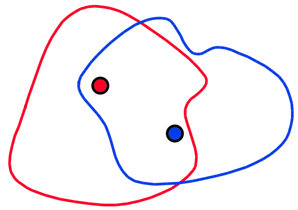
- How to fit Power Control in the hierarchical OSI framework?

Bidirectional links

- Bidirectional links are good
  - If I can hear you, you can hear me
- Networks with wires have bidirectional links
- In wireless networks bidirectional links result when
  - Nodes have the same transmission range

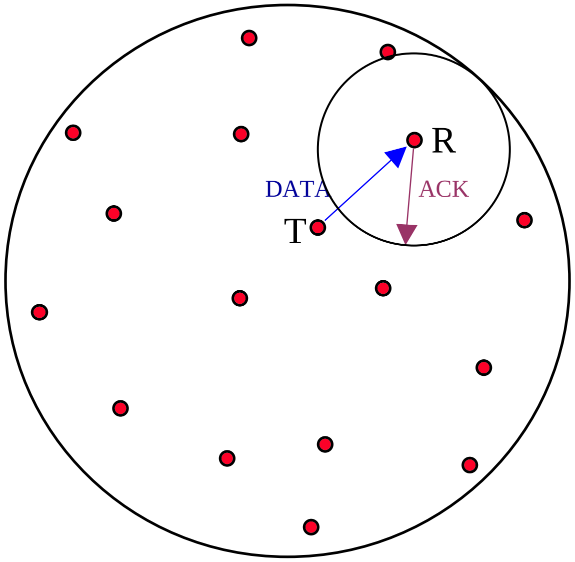


  - Identical nodes use the same power
    - » Even if range is not the same in all directions



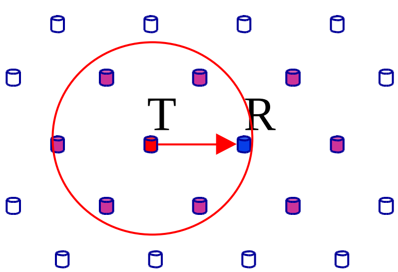
The need for a common range: Link level acknowledgments

- Due to unreliability of wireless medium, link-level acknowledgments are needed at MAC Layer (I believe)
  - If ACK has smaller range, then it is not heard by transmitter

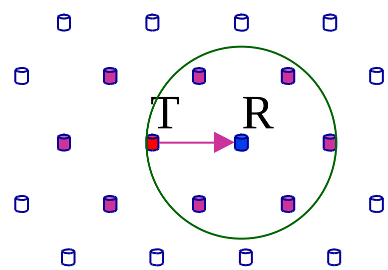


Media Access Control: The IEEE 802.11 handshake

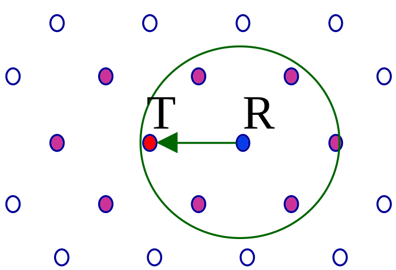
RTS - Neighbors of Transmitter are silenced



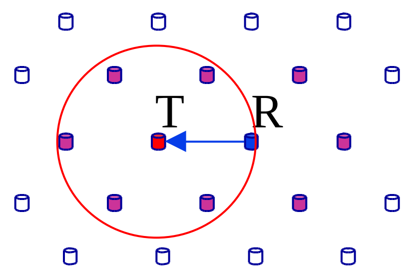
Data is sent



CTS - Neighbors of Receiver are silenced

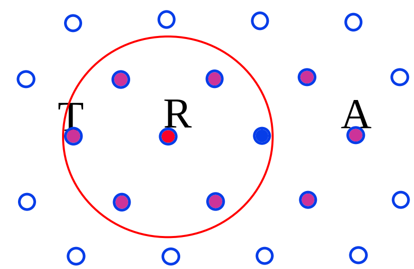


ACK is returned

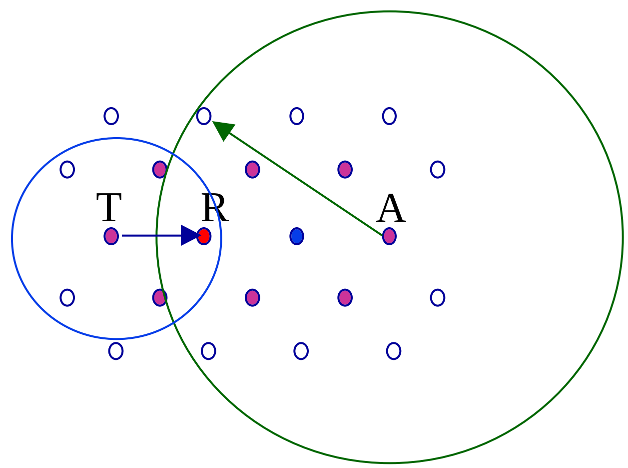


The need for a common range: IEEE 802.11 MAC

- Suppose Range(R) < Range (A)

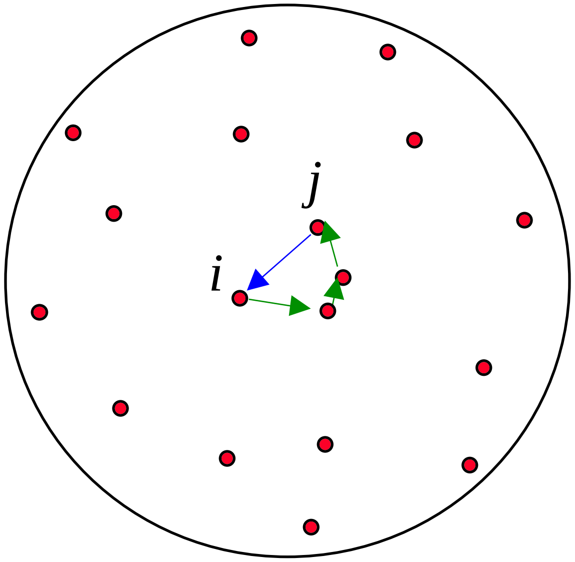


- Suppose A cannot hear R, but R can hear A
  - When R sends CTS
  - Neighbors in CTS range of R are silenced
  - But A is not silenced
  - When A transmits
  - Collision occurs at R

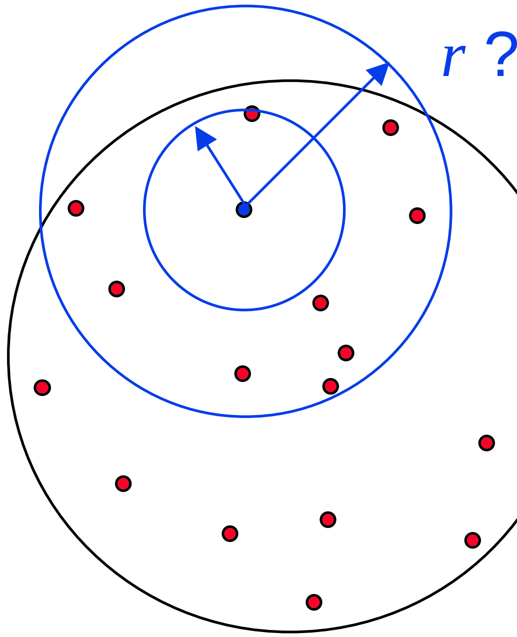


The need for a common range: Distributed Bellman Ford

- $V_i = \text{Min}_j\{c_{ij} + V_j\}$
- But $c_{ij} \neq$ cji
- So $c_{ji} + V_i \neq c_{ij} + V_j$
- Also support for ARP, RARP, etc



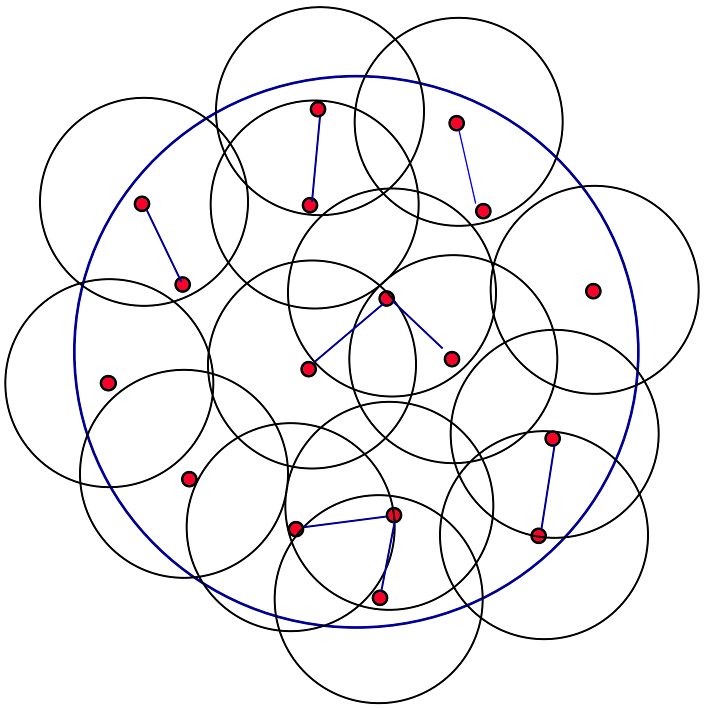
What is the common range to use?

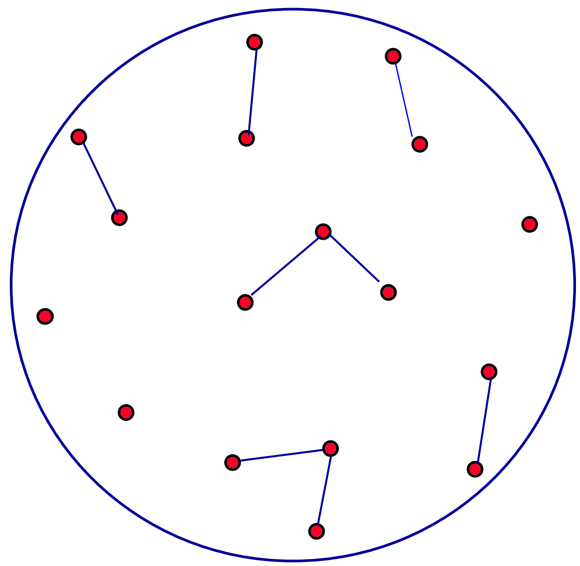


- What happens when the range is too small?
- What happens when the range is too large?

When common range is too small: Network gets disconnected

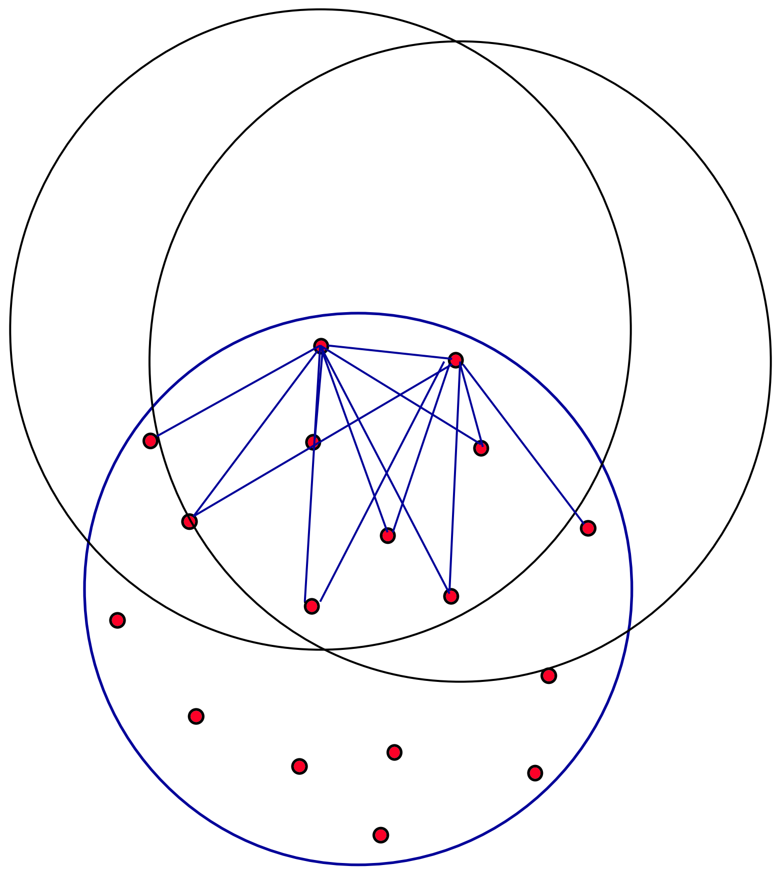
- When common range is too small
  - Network becomes disconnected





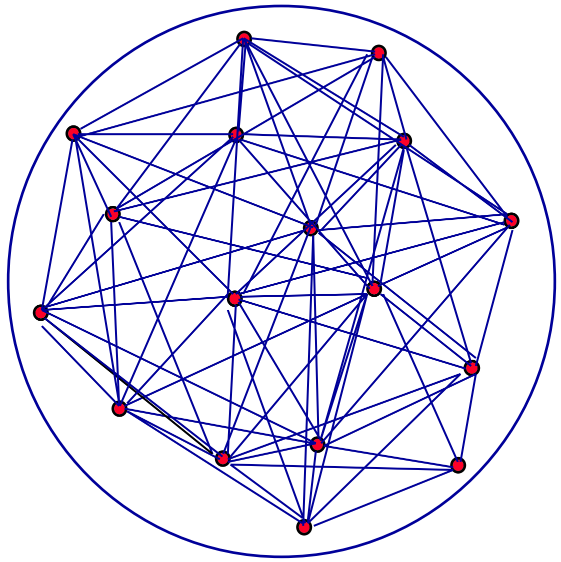
When the range is too large: Too much interference

- When common range is too large
  - Too much interference



-Node can receive only when none of its neighbors is transmitting

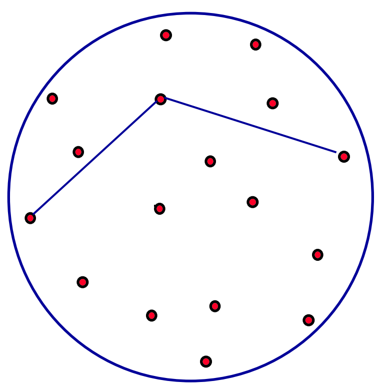
- Capacity of network is reduced
- Capacity = $1/n$



The optimal range for maximum capacity

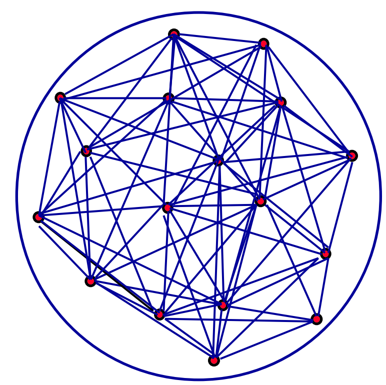
- Tradeoff between long hops and short hops

  - Long hops reduce number of hops and thus the relaying required



  - Number of hops = Relaying burden = $1/r$

  — But they also increase interference



  — Interference r^2

- Net burden r
- Best to use smallest range r

The Network Layer Power Control problem

- Network-wide Power Control problem
  - All nodes need to use common range
  - The common range should be chosen just large enough for network connectivity

- This is a Network Layer problem since connectivity can only be decided at the Network Layer, not below it

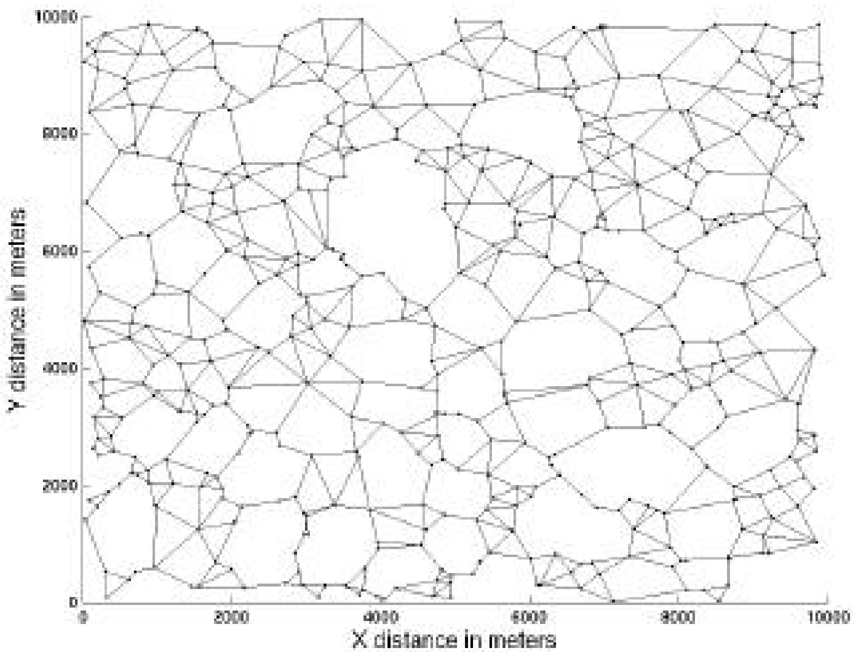
- Interdependence of Routing and Power Control
  - Connectivity determined from existence of routes which depend on power level
  - But choice of power level depends on connectivity

- So joint solution for Power Control and Routing situated at the Network Layer

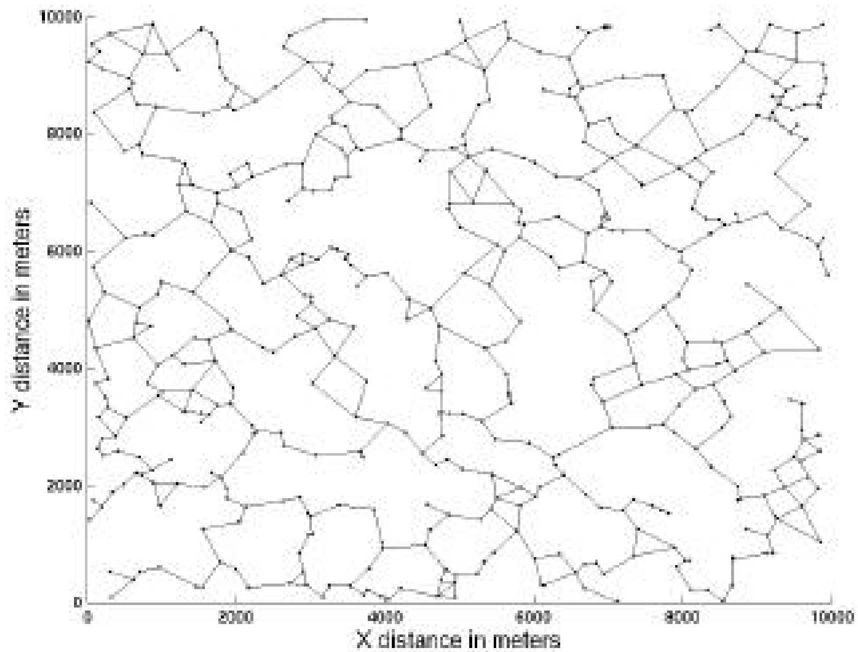
Low common power level also yields power aware routes

- Theorem
  - For propagation path loss $1/\rho^{\alpha}$ with $\alpha \geq 2$ the minimum power routes give a planar graph with straight line edges that do not cross.
  - The graph for $\alpha > 2$ is a subgraph of that for $\alpha = 2$.

$\alpha=2$



$\alpha=4$



Asynchronous distributed operation: Parallel modularity architecture

- Use Parallel Modularity to determine connectivity at different power levels
  - Run routing algorithms at different power levels in parallel
  - Eg: CISCO Aironet 340 cards have four levels: 1, 5, 15, 30mW

1mW

Routing Table for Node G		
Destination	Next node to send to	Distance
A	D	4
B	F	3
C	None	Infinity
D	D	1
E	None	Infinity
F	F	1
G	G	0

5mW

Routing Table for Node G		
Destination	Next node to send to	Distance
A	D	4
B	F	3
C	None	Infinity
D	D	1
E	None	Infinity
F	F	1
G	G	0

15mW

Routing Table for Node G		
Destination	Next node to send to	Distance
A	D	4
B	F	3
C	None	Infinity
D	D	1
E	None	Infinity
F	F	1
G	G	0

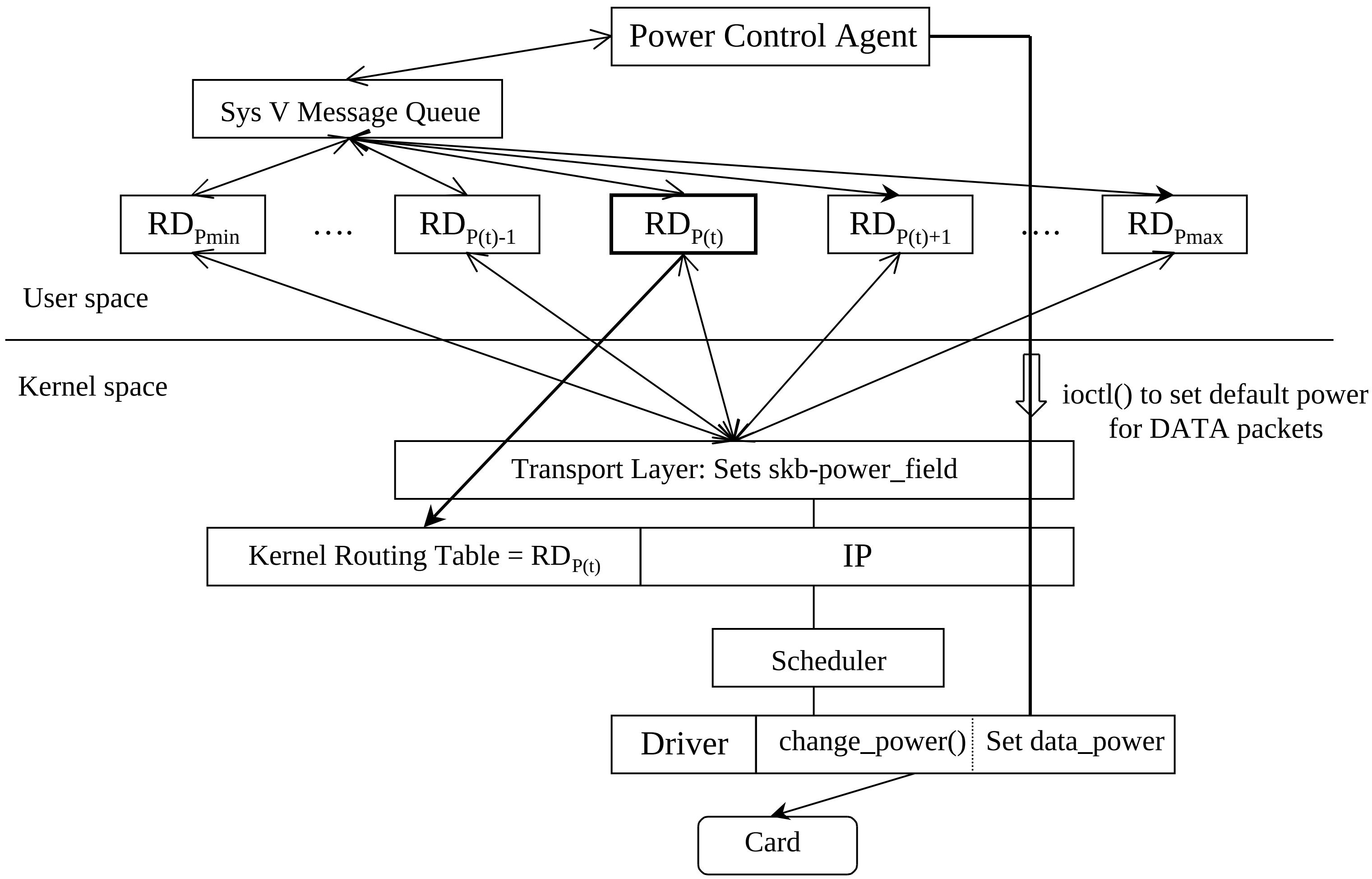
30mW

Routing Table for Node G		
Destination	Next node to send to	Distance
A	D	4
B	F	3
C	None	Infinity
D	D	1
E	None	Infinity
F	F	1
G	G	0

- How to send packets containing routing table information to appropriate table?
  - Use port demultiplexing property of UDP
  - Each routing daemon is simply assigned a port

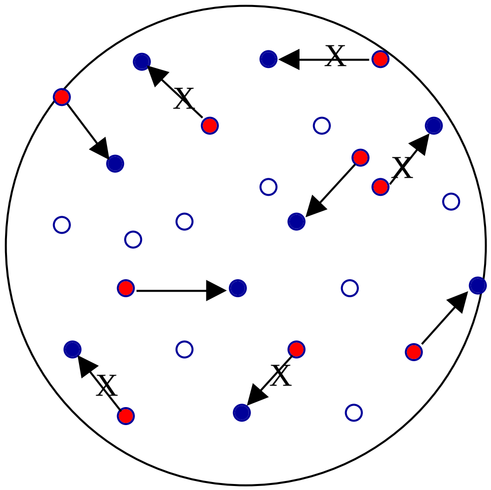
The Common Power (COMPOW) protocol

- Software implementation of COMPOW in the Linux kernel stack



Protocol Design: The SEEDEX Protocol for Media Access Control (RK 2000)

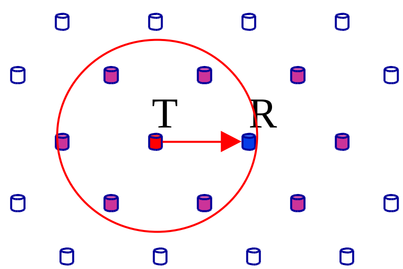
The Media Access Control problem



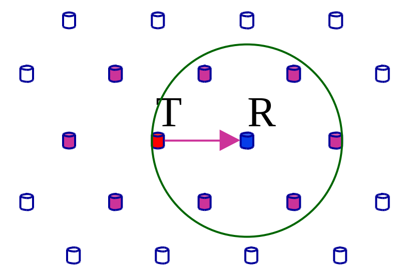
- Wireless is a shared medium
  - There is interference
  - Receiver can receive only if
    none of its other neighbors is transmitting
- A circular problem
  - Communication requires coordination
  - But coordination requires communication
- How to do this in an asynchronous distributed real time fashion?

IEEE 802.11 Protocol: Four phase handshake

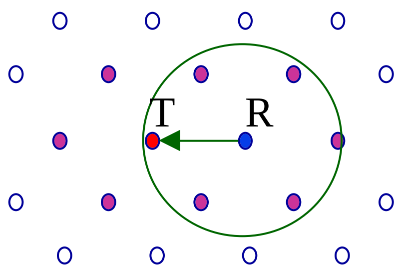
<u>RTS</u> - Neighbors of Transmitter are silenced



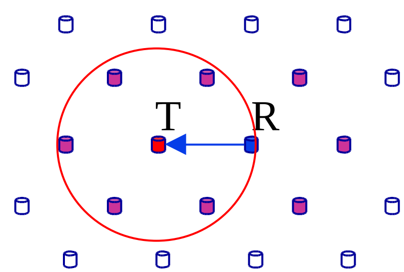
<u>Data</u> is sent



<u>CTS</u> - Neighbors of Receiver are silenced



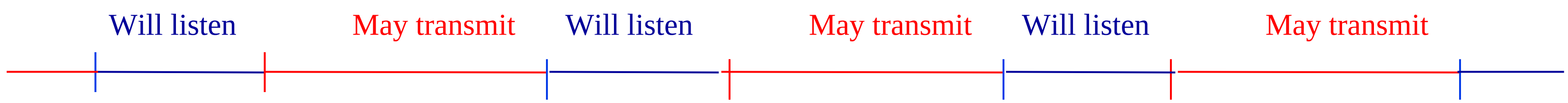
<u>ACK</u> is returned



- <u>Note</u> Two neighborhoods are silenced
  - Could be entire network for a small network. Overhead of about $1/n$
  - Also backoff counters, etc

The SEEDEX Protocol: Publishing schedules

- Suppose all nodes could publish their schedules
  - Schedule = {Times at which node will listen, Times at which node may transmit}

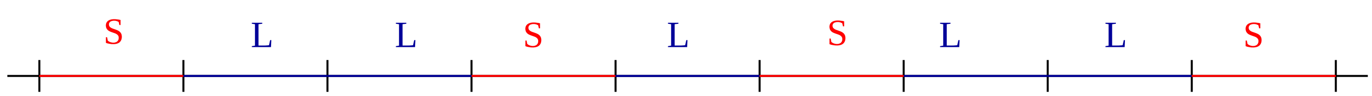


- Then other nodes can intelligently schedule their transmissions

- How do you choose your schedule?
- How to publish it?

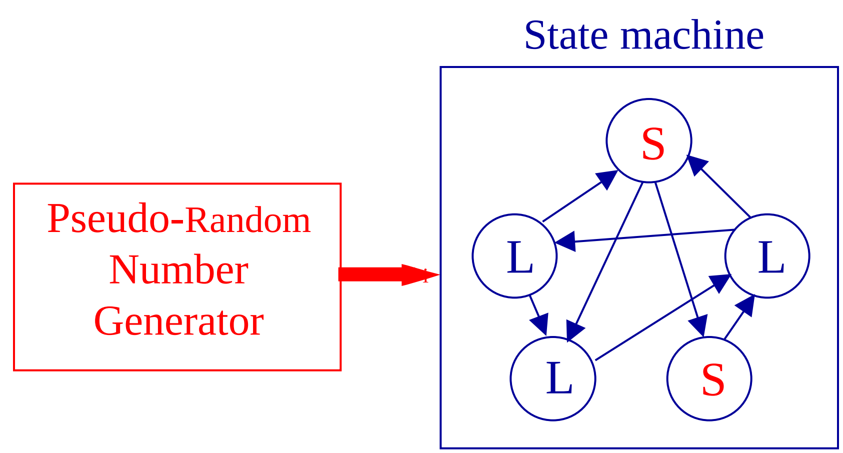
Random schedules

- Random Bernoulli schedule with probabilities p, $1-p$



  - S = *Possibly* Transmit Packet
  - L = Listen for Packets

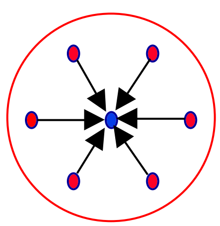
- Or more generally



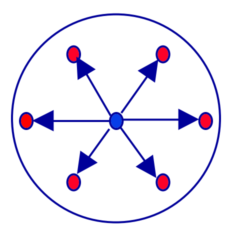
Publishing a schedule without publishing it: Exchanging SEEDs

- Pseudo-Random Number Generators are determined by their <u>seeds</u>
- Nodes only need to <u>exchange</u> their seeds - The SEEDEX protocol
- Nodes need to inform their SEEDS to all their two hop neighbors

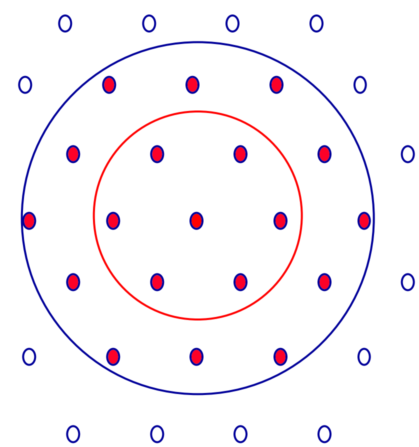
Send all SEEDs of your neighbors to your neighbor



Neighbor sends all SEEDs of its neighbors to you

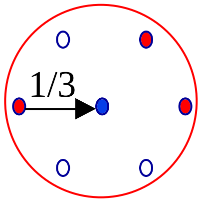


Now you know SEEDs of all your 2-hop neighbors

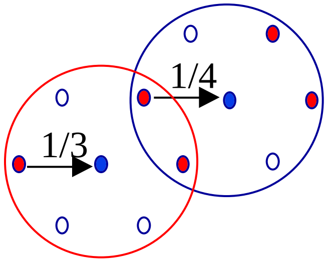


When should you transmit?

- Suppose *m* neighbors of Receiver are in state S
  - Then Transmit with probability $\frac{1}{m+1}$



- However, the other Transmitter may be looking at a different Receiver
  - So you both may use differing transmission probabilities
  - Exact calculations are difficult



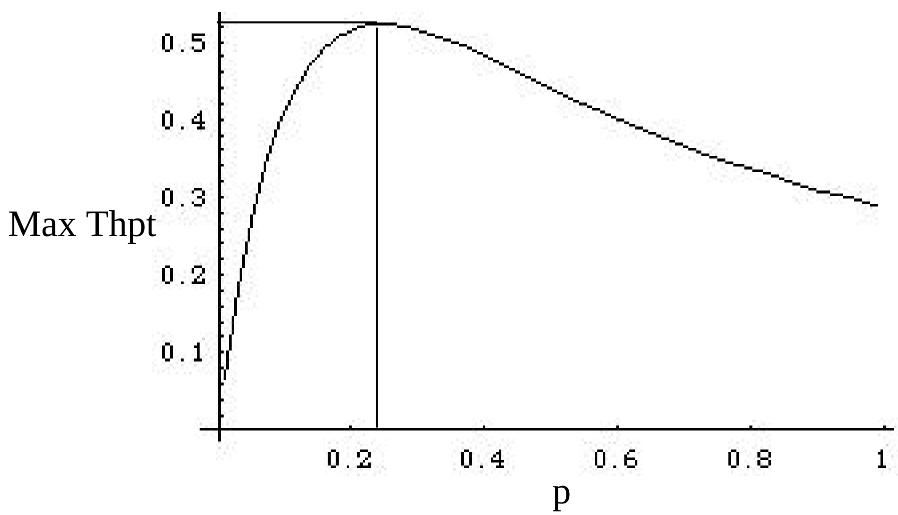
- Use $\frac{\alpha}{m+1}$ where $\alpha \approx 2.5$ in light traffic, $\alpha \approx 1.5$ in heavy traffic

Some calculations and simulations

- An approximate expression:

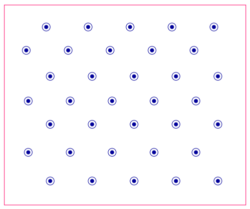
Max Thpt(p, α) = (N+1)*Throughput per Node

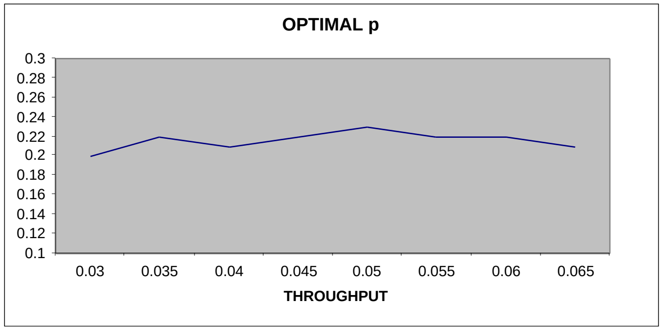
$$= (N+1)\pi_S\pi_L \sum_{m=0}^{N-1} \binom{N-1}{m} \pi_S^{\,m} \pi_L^{\,N-1-m} \frac{\alpha}{m+1}\left(1-\frac{\alpha}{m+1}\right)^m$$



Best p = 0.246
Max Thpt = 52.2%

- Simulation Results on 100 Node System:

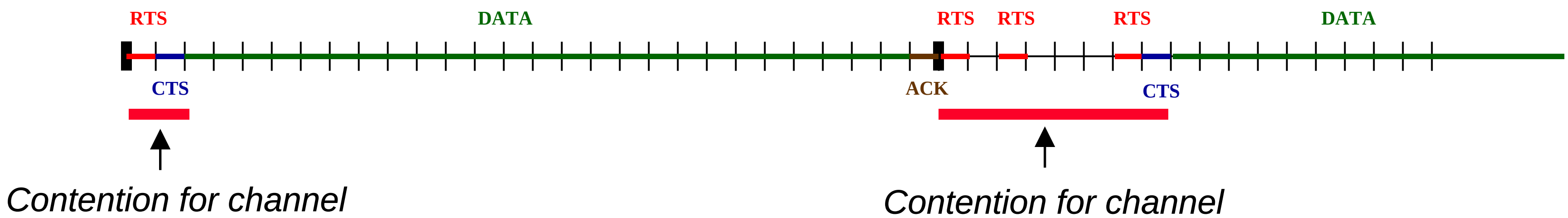




- $p \equiv 0.21$ is a good choice for all levels of demand
- $\alpha \approx 2.5$ (light traffic)
  $\alpha \approx 1.5$ (heavy traffic)

One more idea: Use SEEDEX only for reservation packets

- Use SEEDEX only for the RTS



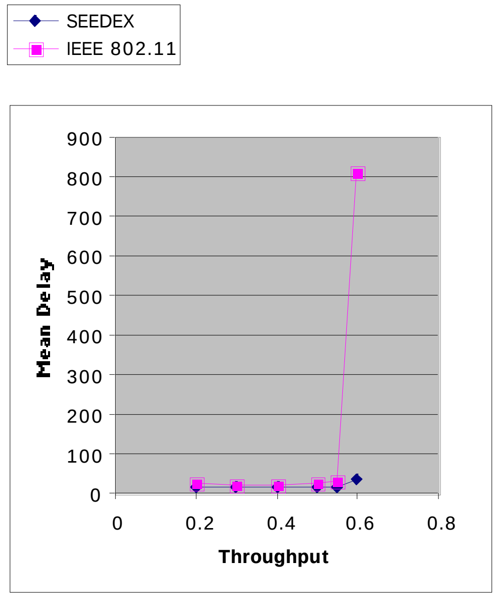
- Thus long DATA slots are not wasted

- The SEEDEX-R Protocol

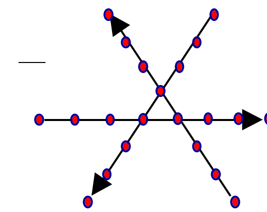
Comparison of SEEDEX and IEEE 802.11 on ns

Mean Delay

Throughput	SEEDEX	IEEE 802.11
0.2	15.52	24.34
0.3	15.74	21.56
0.4	15.50	20.34
0.5	15.54	24.04
0.55	15.64	30.13
0.6	33.63	809.09

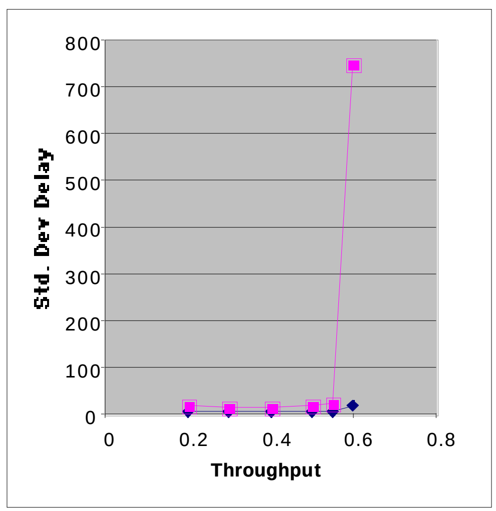


- Three contending flows

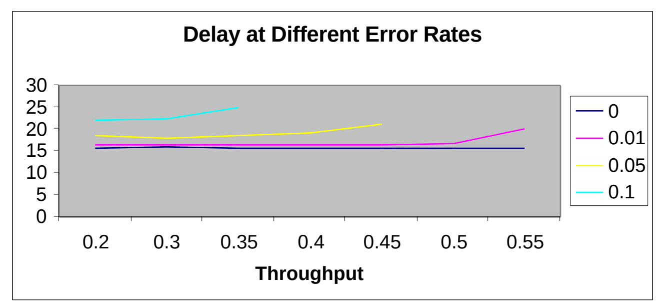


Std Dev of Delay

Throughput	SEEDEX	IEEE 802.11
0.2	2.85	18.68
0.3	3.08	13.61
0.4	2.90	11.59
0.5	2.97	15.54
0.55	3.29	21.01
0.6	18.93	748.77



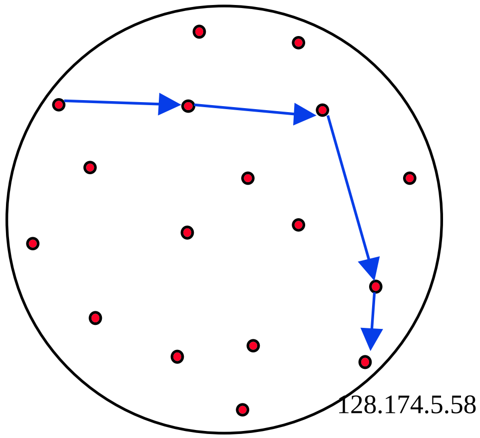
Mean Delay vs. Channel Error Rate



Protocol Design: The STARA Protocol for Routing (GK 1998)

The Routing Problem

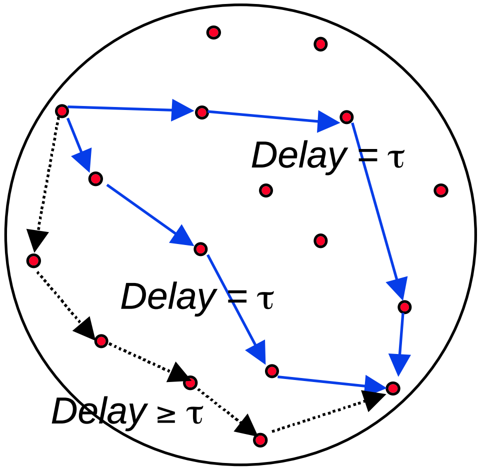
- How to find routes between sources and destinations of packets?
  - In wireless networks an IP address (such as 128.174.5.58) does not indicate its location
  - It does not tell us how to reach the destination



- Can we design an adaptive distributed asynchronous routing algorithm that adapts routes
  - To the topology of the network
  - To the prevailing traffic conditions, e.g., delay adaptive?

The Wardrop equilibrium

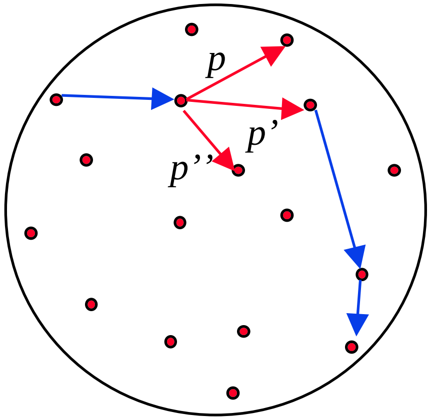
- Goal: Route traffic from origin to destination such that
  - All utilized routes have the same mean delay
  - All unutilized routes have larger potential mean delay



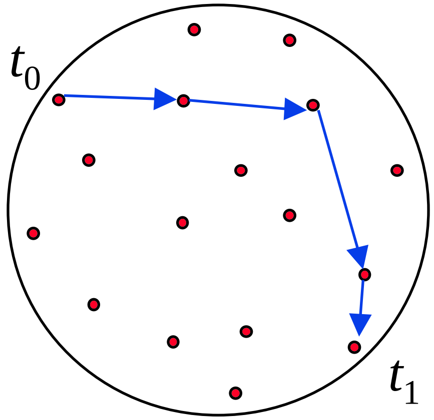
- Called the Wardrop equilibrium in transportation theory

STARA: A System and Traffic Adaptive Routing Algorithm

- Adapt proportions of traffic carried along routes so that all utilized routes have same mean delay



- Obtain an estimate of round trip delay
  - Time stamp packet t_0 when it is sent out
  - Time stamp packet t_1 when it is received
- <u>However</u>:
  - Difference t_1 - t_0 ≠ Delay
  - Since clocks at Origin and Destination generally have different offsets



The basic adaptation algorithm

- D_{ij}^{d} = Estimate of delay from i to d via j
  - D_{ij}^{d}(new) = (1-λ) D_{ij}^{d}(old) + λ (Latest Observed D_{ij}^{d})
- D_{i}^{d} = Estimate of mean delay from i to d over all routes
  - D_{i}^{d} (new) = $\sum_j p_{ij}^{d}$(new) D_{ij}^{d}(new)
- p_{ij}^{d} = Proportion of traffic from i to d routed via j
  - p_{ij}^{d}(new) = p_{ij}^{d} (old) + α p_{ij}^{d} (old) (D_{i}^{d}(new) - D_{ij}^{d}(new))
  - Note: Subtraction eliminates clock offsets!
  - Also we are equalizing delays!
- Theorem (BK 2001): Above algorithm with some modifications Cesaro equilibrates to a Wardrop solution

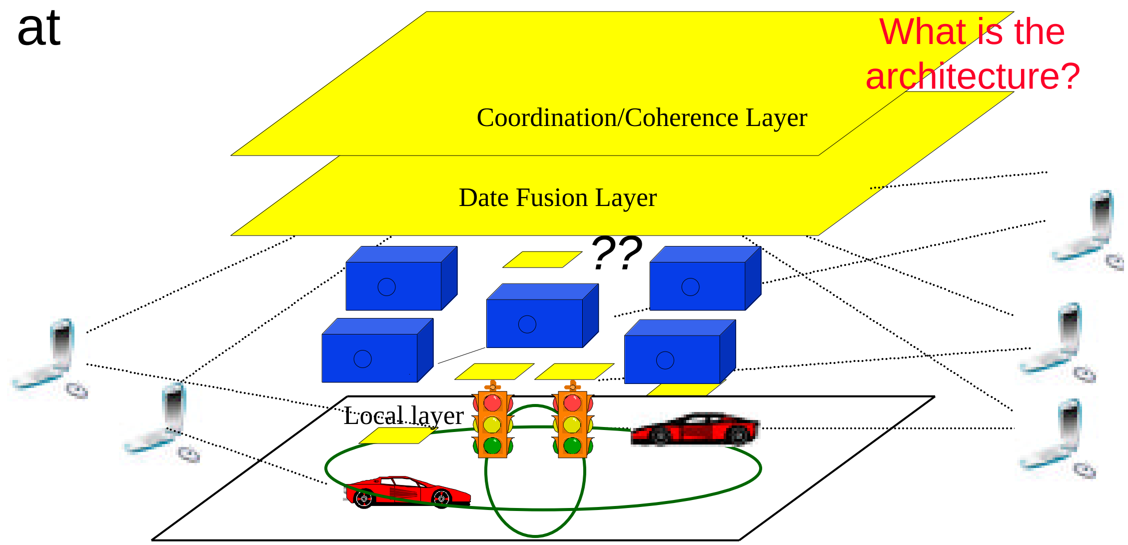
The architecture of convergence

Towards convergence of communication, computing and control

- Embedded systems have proliferated, in isolation
- Wireless networks are on the cusp of takeoff
  - Embedded systems can be interconnected wirelessly
  - Each embedded device can be sensor or an actuator
- Systems of wirelessly interconnected sensors and actuators
- Convergence of sensing, actuation, communication and computation
- Question: How do we organize distributed real-time systems?

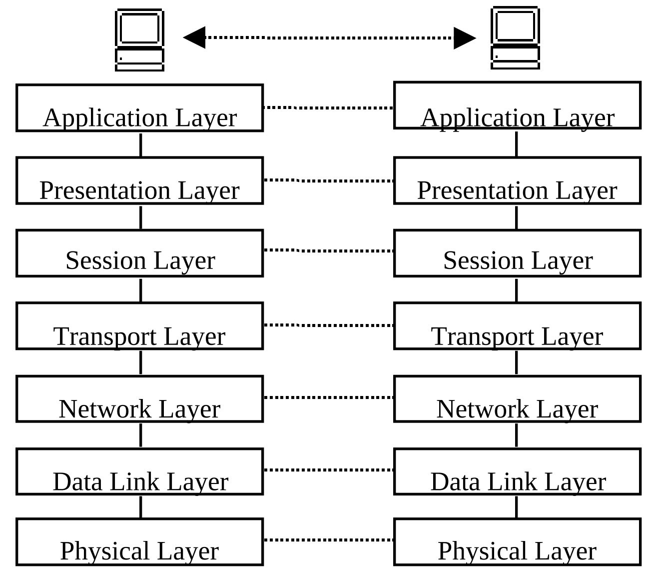
What are the right abstractions? What is the architecture?

- A testbed for convergence at University of Illinois
  - Eg. Suppose traffic lights and cars and sensors can talk to each other
  - What should be the architecture of the system?



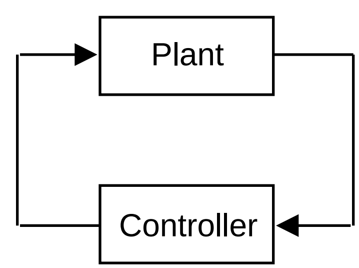
The importance of architecture

- Success of Internet is due to its architecture
  - Notion of peer-to-peer protocols
  - Hierarchy of layers
  - Allows plug-and-play
  - Proliferation of technology



- Success of serial computing
  - von Neumann bridge (Valiant)
  - Hardware designers and software designers need only to conform to abstractions of each other

- Control system paradigm
  - Plant and controller separation



To obtain papers

- Papers can be downloaded from

  http://black.csl.uiuc.edu/~prkumar

- For hard copies send email to

  prkumar@uiuc.edu