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

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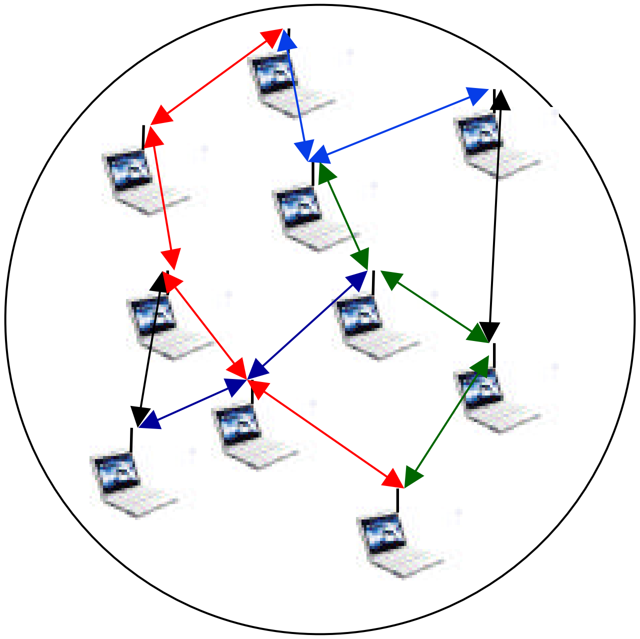
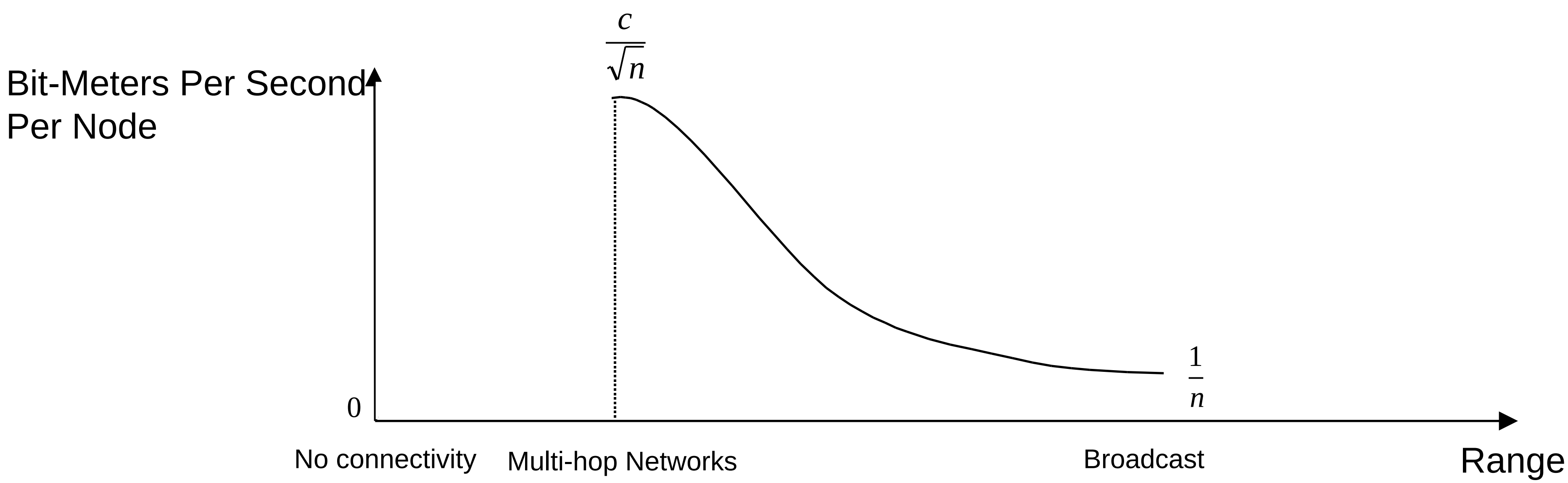
Ad Hoc Networks

- Ad Hoc Networks are communication networks formed by nodes with radios
  - They function by multi-hop transport
    - Nodes relay packets until they reach their destinations
  - They should be spontaneously deployable anywhere
    - On a campus
    - In an office building or home
    - In a meeting room
    - 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



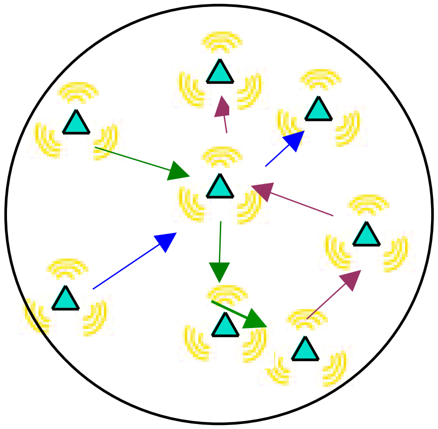
Why multi-hop?



- Multi-hop increases traffic carrying capacity

Issues: Analysis, Protocols and Architecture of convergence

- How much traffic can wireless networks carry?
  - Wireless is a shared medium
    - How many bits can get transmitted at a cocktail party?



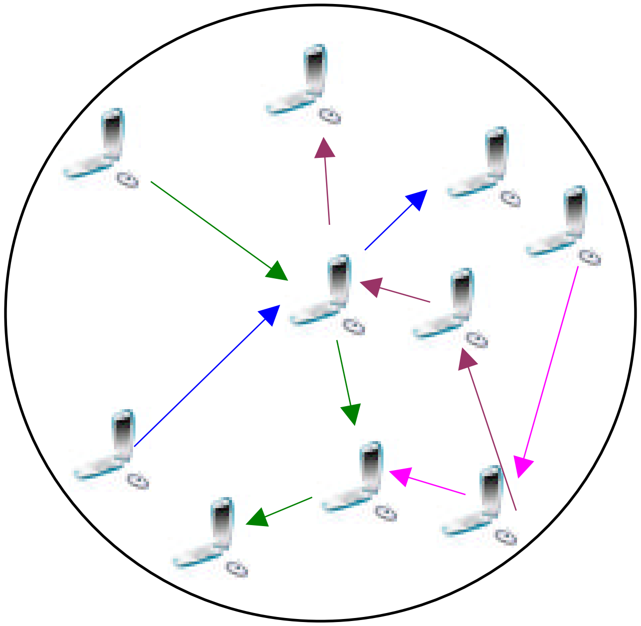
- How should they be operated?
  - Design of operating protocols which adapt to the environment
    - Power Control
    - Media Access Control
    - Routing

- Towards convergence of communication, computing and control
  - Abstractions and Architecture

Analysis: Scaling Laws

How much traffic can wireless networks carry?

- Model
  - Disk of area A sq.m
  - n nodes
  - Each can transmit at W bits/sec
- Shared wireless channel:
  - Packets are successfully received when there is no local interference



- What can they provide?
  - Throughput for each node: Measured in Bits/Sec
  - Traffic carrying capacity of entire network: Measured in Bit-Meters/Sec
  - Scaling with the number of nodes n

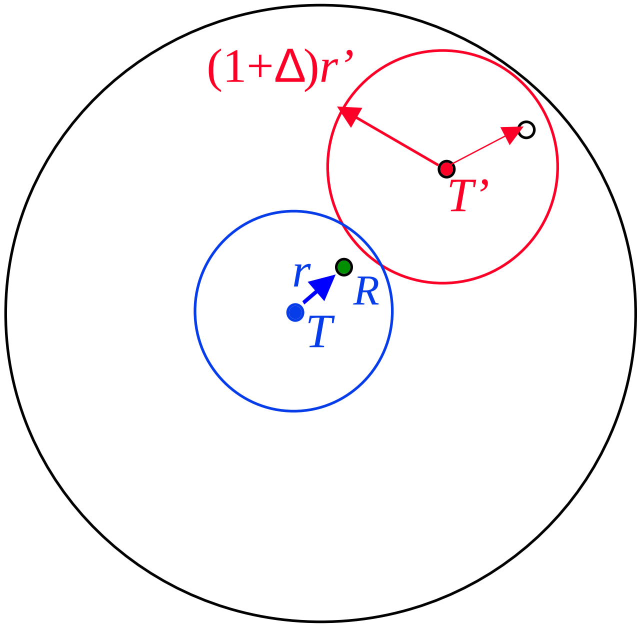
When are packets successfully received?

- <u>Protocol Model</u>

  Receiver R should be

  (i) within range r of its own transmitter T

  (ii) outside footprint $(1+\Delta)r'$ of any other transmitter T' using range r'



- Similar results when the Signal-to-Interference Ratio is required to be larger than a required value:

$$\text{SIR Ratio} = \frac{P_i r_i^{-\alpha}}{N + \sum_{j \neq i} P_j r_j^{-\alpha}} \geq \beta$$

Best possible scenario

- Optimal network
  - » Optimally located nodes, destinations, demands for OD-pairs
  - » Optimal spatial and temporal scheduling, routes, ranges for each transmission

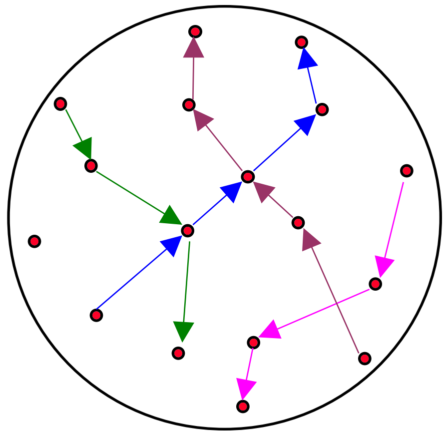
- Protocol Model: Network can transport $\Theta\left(W\sqrt{An}\right)$ bit-meters/sec

$$\frac{W}{1+2\Delta}\frac{n}{\sqrt{n}+\sqrt{8\pi}} \leq \text{Best case capacity for Protocol Model} \leq \sqrt{\frac{8}{\pi}}\frac{W}{\Delta}\sqrt{n} \quad \text{bit-meters/sec}$$

- If equitably divided, each node can send $\Theta\left(W\sqrt{\frac{A}{n}}\right)$ bit-meters/sec

Random network scenario

- n nodes randomly located
  - Each node chooses random destination
  - Equal throughput λ bits/sec for all OD pairs
  - Each node chooses same range r



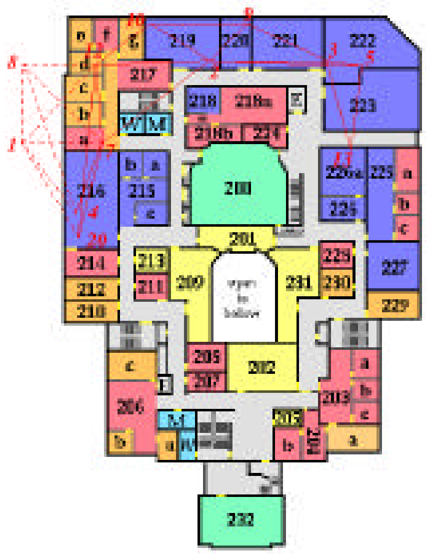
- Best choice of spatio-temporal scheduling, ranges and routes
- Each node can send $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$ bits/sec { Random networks are nearly best; Also lowest common range for connectivity is optimal
- Definition of capacity

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

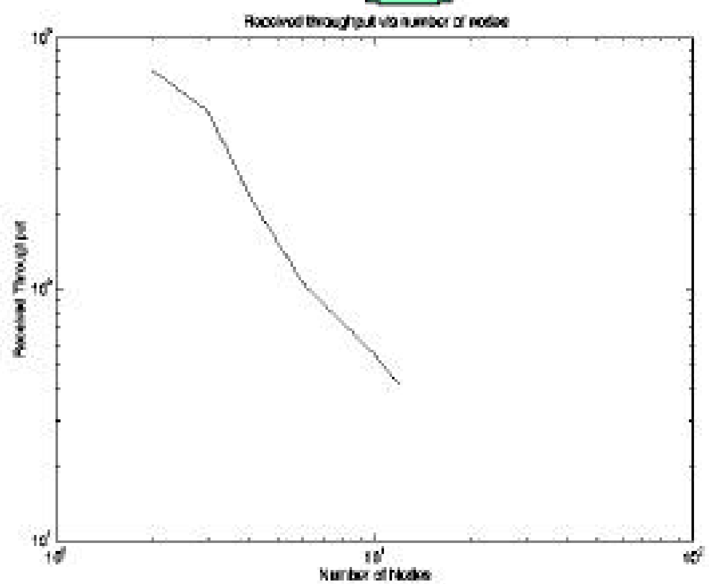
$$\lim_{n \to \infty} P\left(\lambda(n) = \frac{c'}{\sqrt{n \log n}} \text{ is feasible}\right) = 0$$

{ Sharp cutoff phenomenon

Experimental scaling law



Log(Thpt)



Log(Number of Nodes)

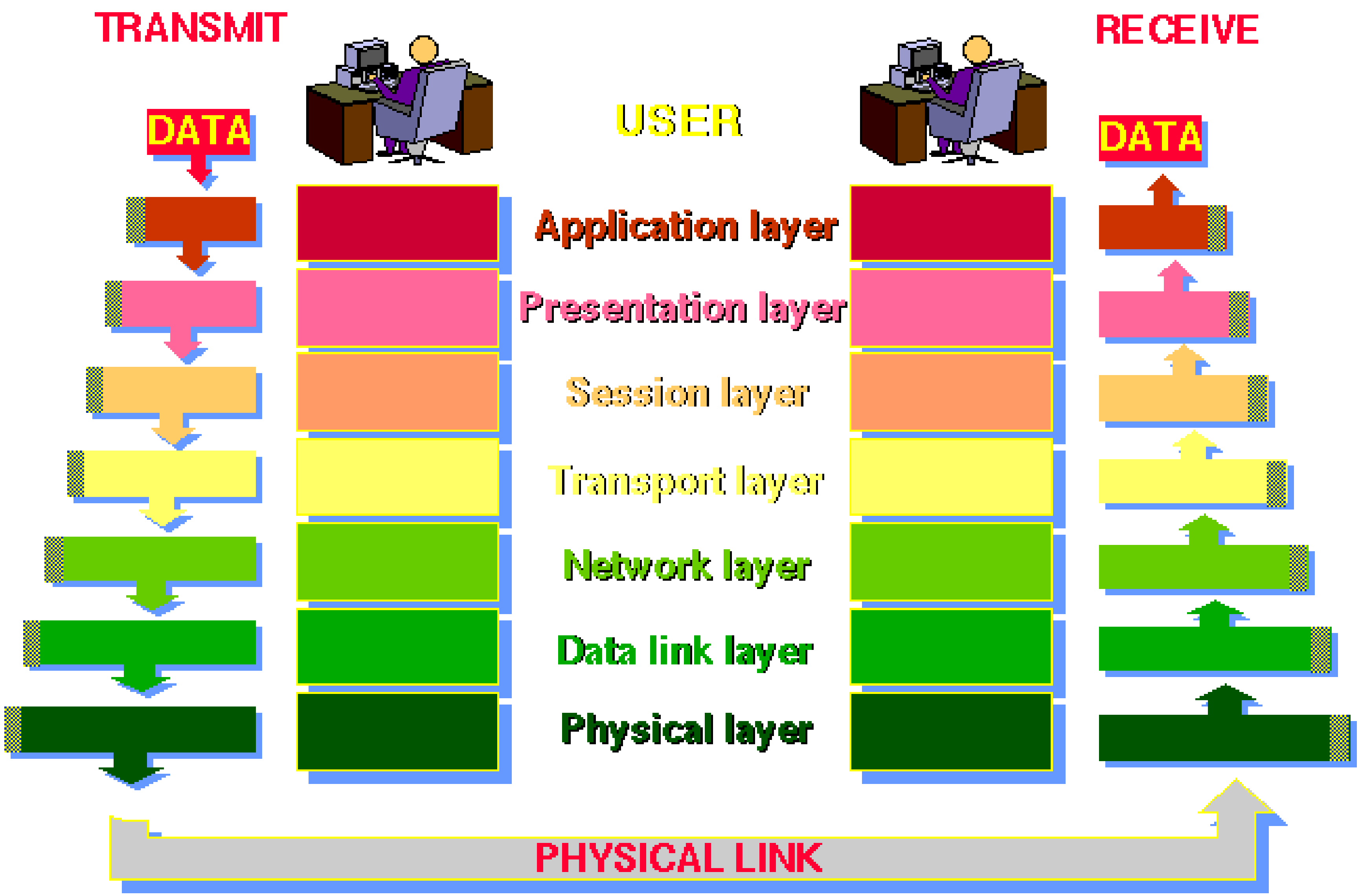
- Throughput = $2.6/n^{1.68}$ Mbps per node
  - No mobility
  - No routing protocol overhead
    - Routing tables hardwired
  - No TCP overhead
    - UDP
  - IEEE 802.11
- Why $1/n^{1.68}$?
  - Much worse than optimal capacity = $c/n^{1/2}$
  - Worse even than $1/n$ timesharing
  - Perhaps overhead of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

How to operate ad hoc networks?

- Design operating protocols for
  - Power Control
    - How much power should be used on each broadcast?
  - Media Access Control
    - When should you talk at a cocktail party to avoid interfering with others?
  - Routing
    - How should packets find their destinations?
    - An address does not indicate where a node is located or how to get there

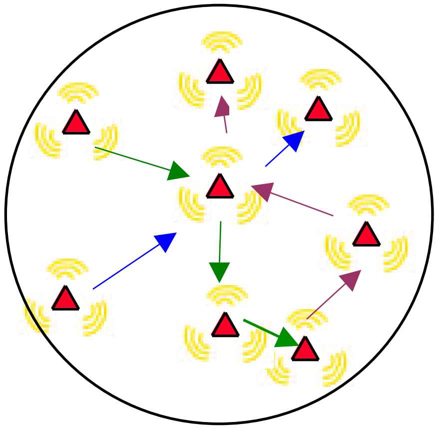
Protocol Design: Power control

THE 7 LAYERS OF OSI

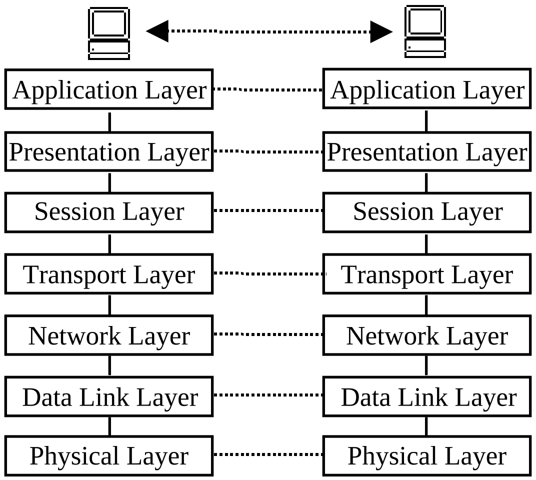


The Power Control problem

- 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



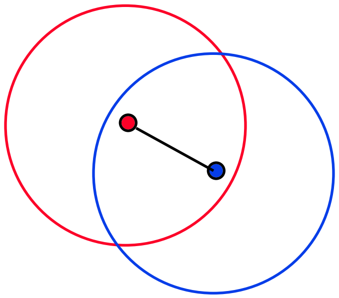
- How to fit Power Control in the hierarchical OSI framework?

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

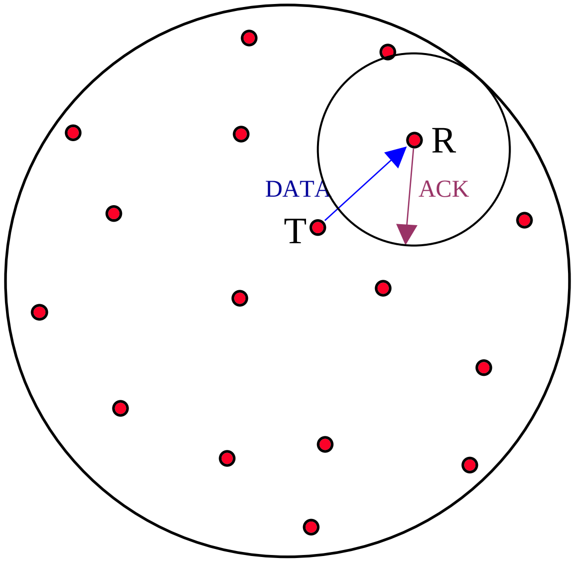


  - Identical nodes use the same power
    - » Even if range is not the same in all directions

The need for a common range: Link level acknowledgments

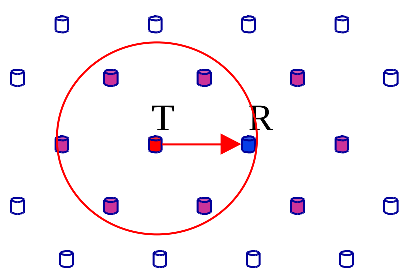
- Due to unreliability of wireless medium, link-level acknowledgments are needed at MAC Layer (I believe)

  – If ACK has smaller range, then it is not heard by transmitter

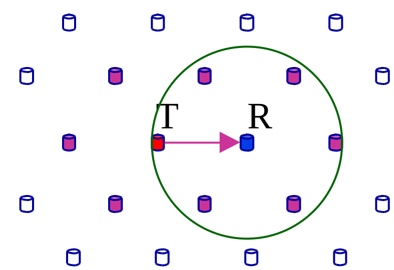


Media Access Control: The IEEE 802.11 handshake

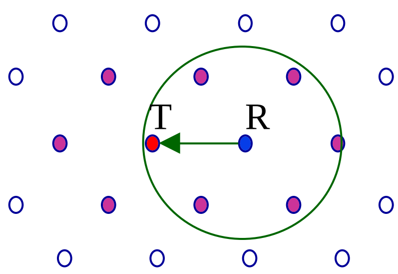
RTS - Neighbors of Transmitter are silenced



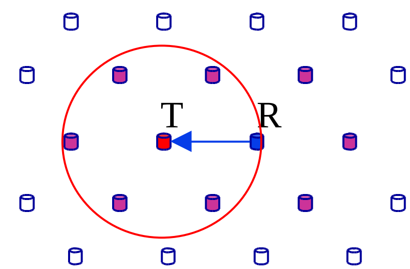
Data is sent



CTS - Neighbors of Receiver are silenced



ACK is returned



The need for a common range: IEEE 802.11 MAC

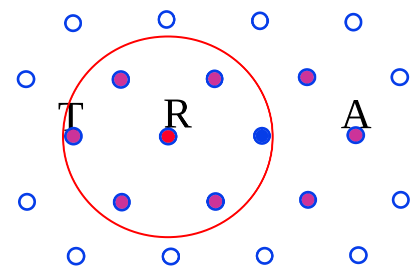
- Suppose Range(R) < Range (A)

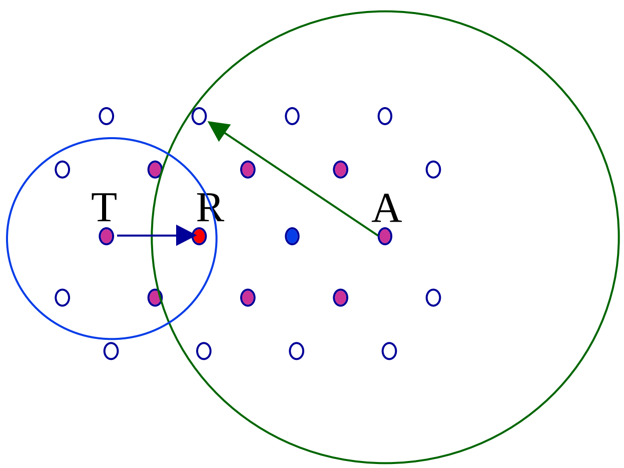
- Suppose A cannot hear R, but R can hear A

  - When R sends CTS
  - Neighbors in CTS range of R are silenced

  - But A is not silenced

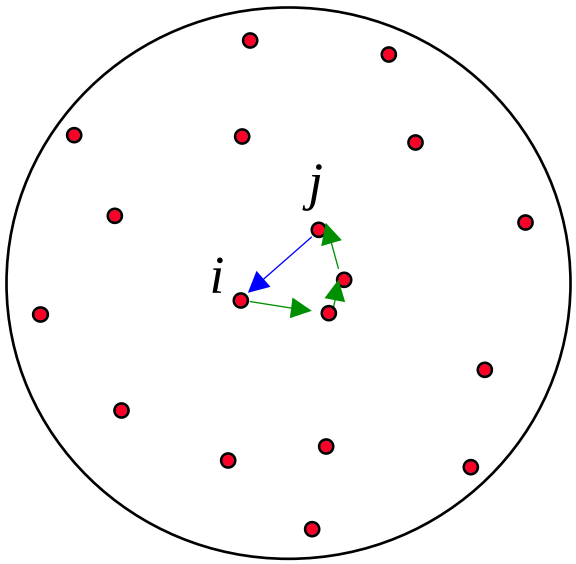
  - When A transmits
  - Collision occurs at R





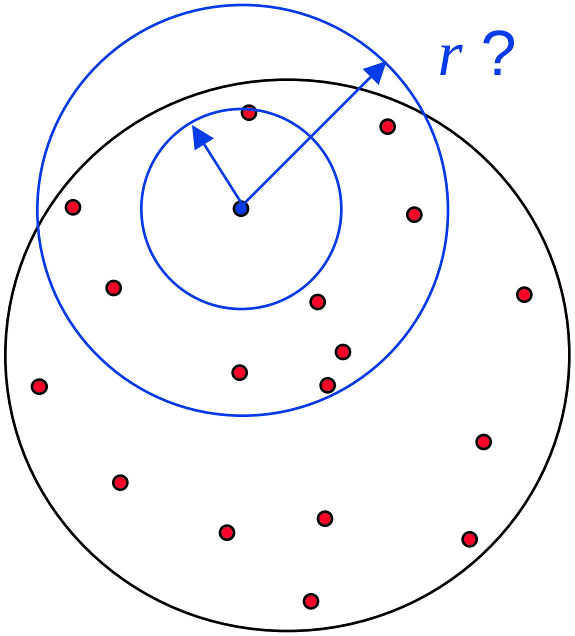
The need for a common range: Distributed Bellman Ford

- $V_i = \text{Min}_j\{c_{ij} + V_j\}$
- But $c_{ij} \neq c_{ji}$
  - So $c_{ji} + V_j \neq c_{ij} + V_j$
  - .....



- Also, support for ARP, RARP, etc

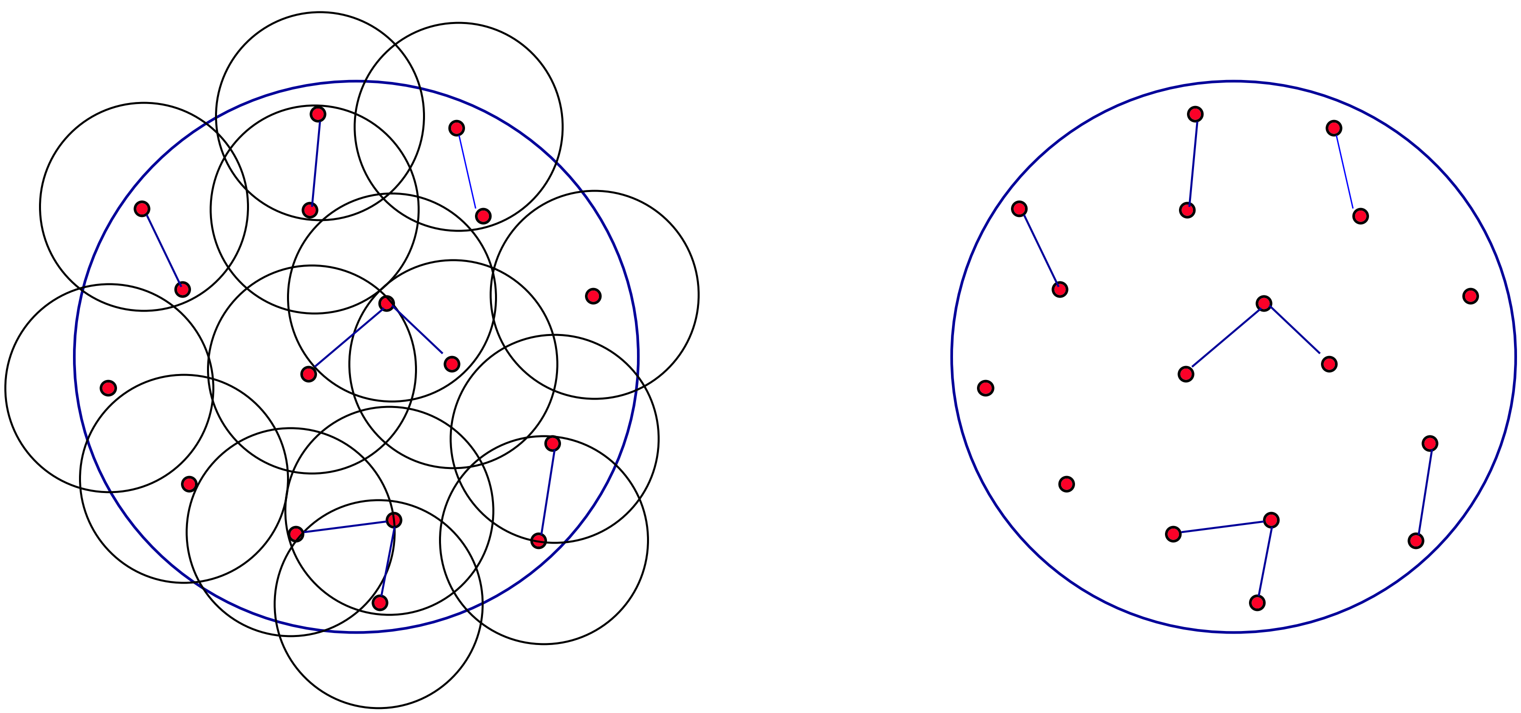
What is the common range to use?



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

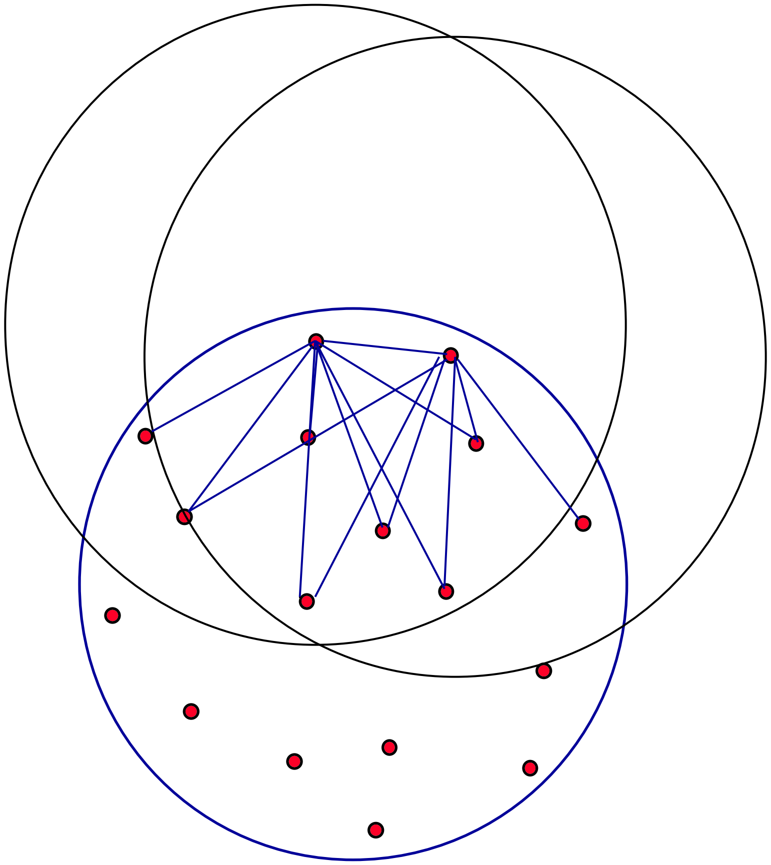
When common range is too small: Network gets disconnected

- When common range is too small
  - Network becomes disconnected



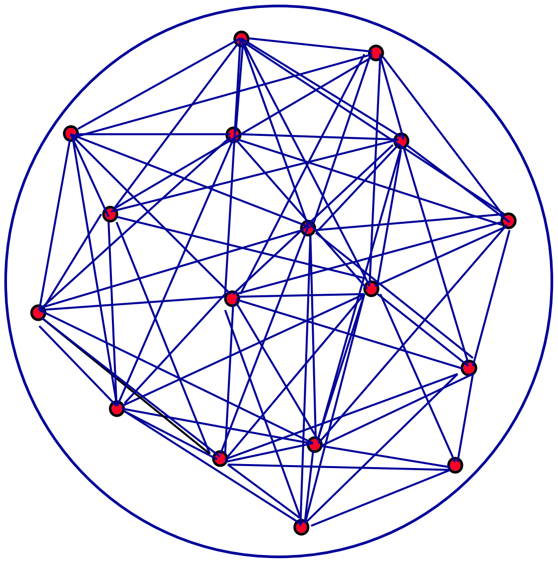
When the range is too large: Too much interference

- When common range is too large
  - Too much interference



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

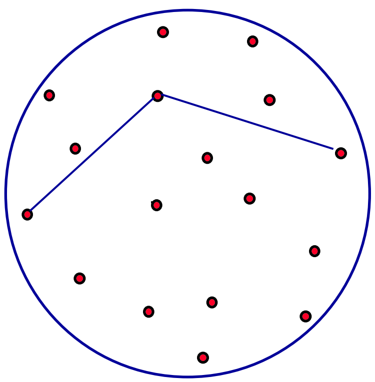
- Capacity of network is reduced
- Capacity = $1/n$



The optimal range for maximum capacity

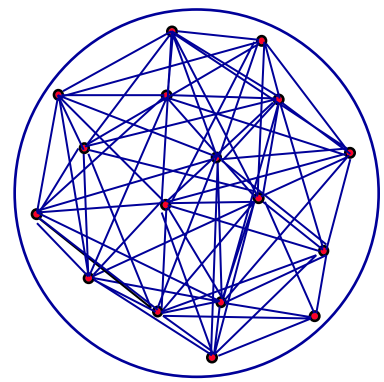
- Tradeoff between long hops and short hops

  – 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

Common power level: Impact on capacity

- Theorem: Best case capacity
  - Optimally located nodes, destinations, demands for OD-pairs
  - Optimal spatio-temporal scheduling, routes, ranges for each transmission
  - Each node obtains $\Theta\left(\frac{1}{\sqrt{n}}\right)$ bits/sec

- Theorem: Random networks
  - Randomly located nodes and destinations
  - Each node chooses same range *r*
  - Each node obtains $\Theta\left(\frac{1}{\sqrt{n \log n}}\right)$ bits/sec

- Only $\sqrt{\log n}$ factor difference between common and different power levels
- Low common power is asymptotically nearly capacity optimal

Common power level: Impact on Media Access Control efficiency

- Low common power level also enhances efficiency of MAC layer
  - Contention within range = # nodes within range × # hops × Throughput

$$= \left(\frac{\pi r^2 n}{A}\right) \times \left(\frac{L}{r}\right) \times W \quad = \quad cr$$

  - Minimized when r = small

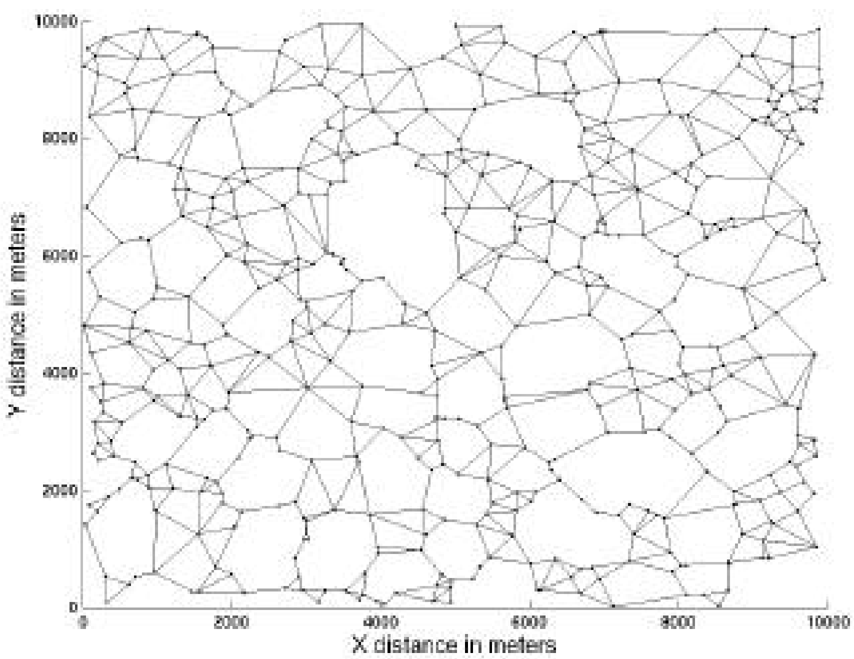
- Theorem: Smallest possible $r(n)$ for connectivity
  - Consider $\pi r^2(n) = \frac{\log n + k(n)}{n}$
  - Then $\lim_n P(\text{Connected network}) = 1$ if and only if $\limsup k(n) = +\infty$.

- A common range $\Theta\left(\sqrt{\frac{\log n}{n}}\right)$ is also capacity optimal

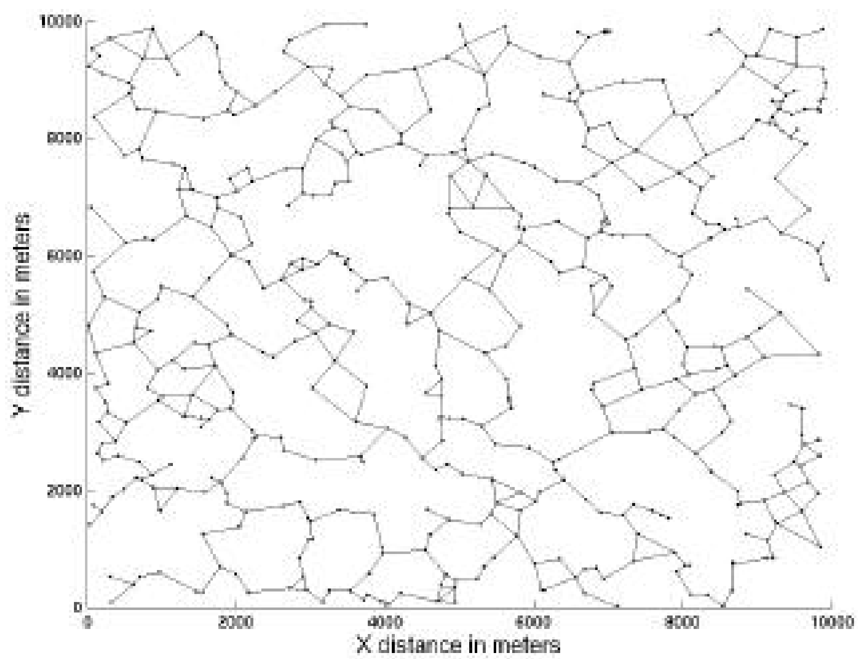
Low common power level also yields power aware routes

- Theorem
  – For propagation path loss $1/r^{\alpha}$ 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

- Nodes may be operating at different power levels
  - How to determine connectivity at a power level?
- Solution: Use Parallel Modularity
  - 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

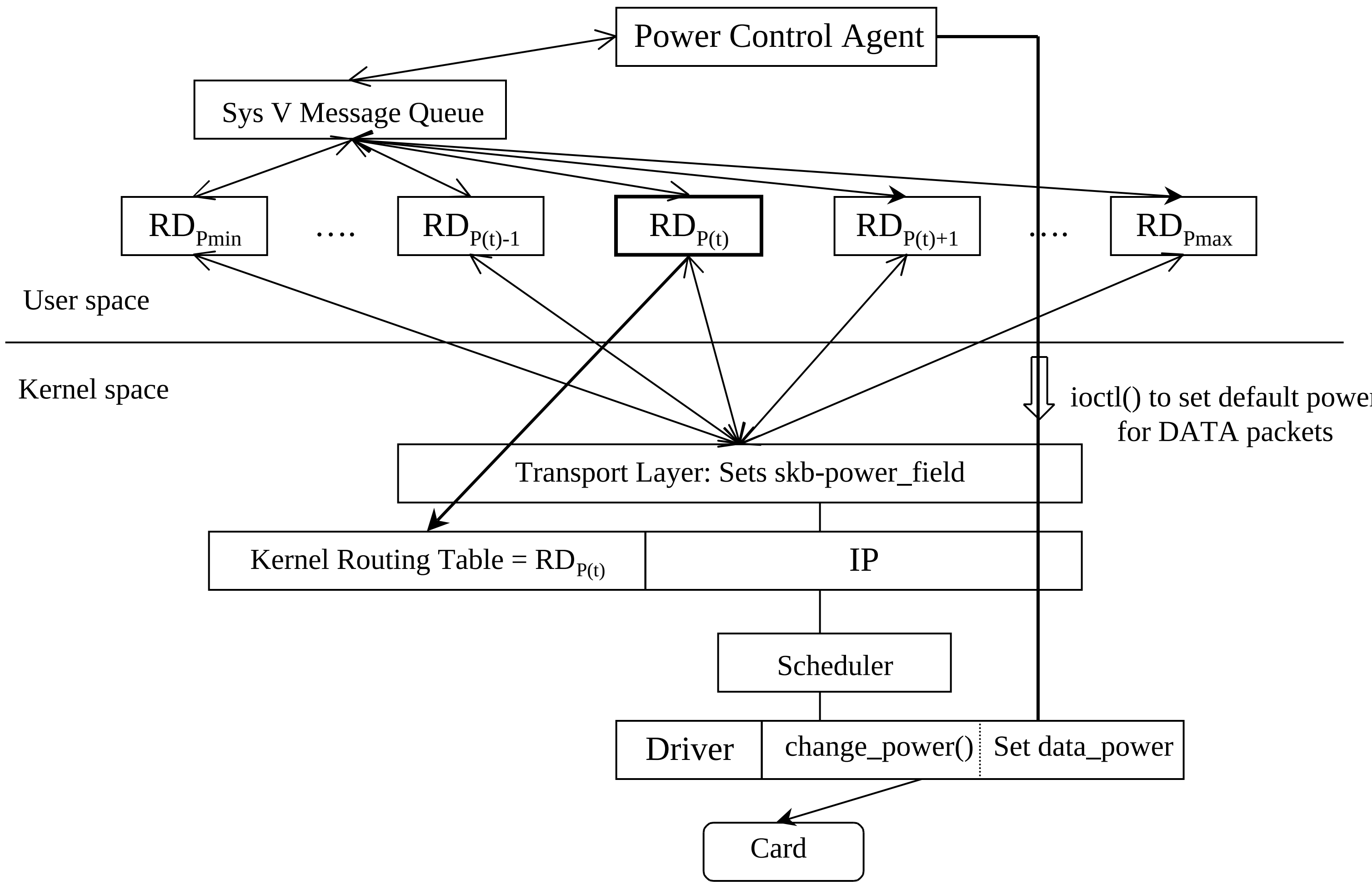
30mW

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 routing table control packets 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: Media Access Control

The Medium Access Control (MAC) Problem

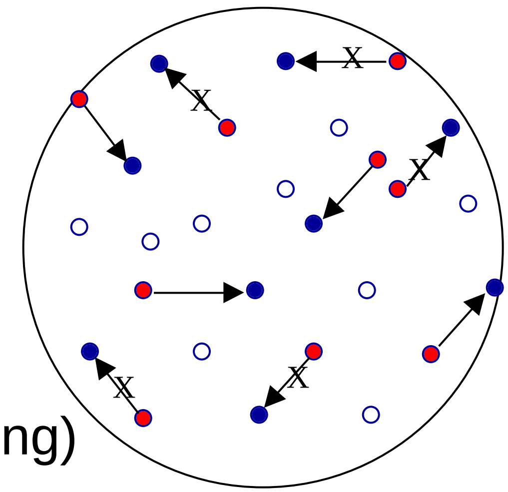
- When should a node broadcast?

Or

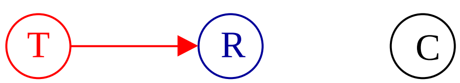
- When should you talk at a cocktail party?
  - You don't want to interfere with others talking to each other
  - You don't want others to interfere with you
- A circular problem
  - Communication requires coordination
  - But coordination requires communication
- How to do this in an asynchronous distributed real time fashion?

The Media Access Control problem

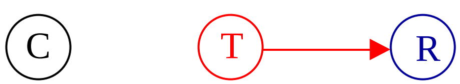
- Wireless is a shared medium
  - There is interference
  - Receiver can receive only if none of its other neighbors is transmitting



- Just listening before you talk (called carrier sensing) will not work, or may be unnecessary
  - Called the hidden terminal problem
  - The conflicting carrier may be unheard

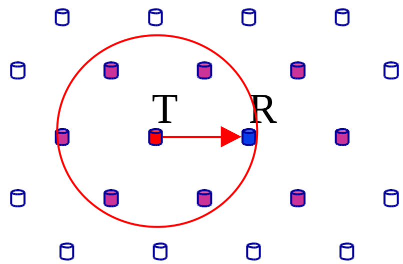


  - Or a carrier that is heard may not interfere with your intended receiver

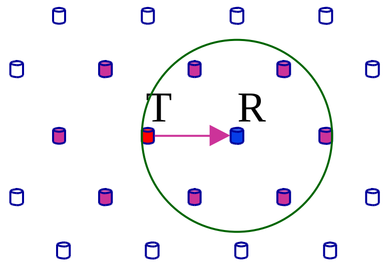


IEEE 802.11 Protocol: Four phase handshaking

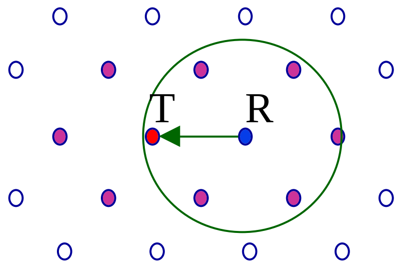
RTS - Neighbors of Transmitter are silenced



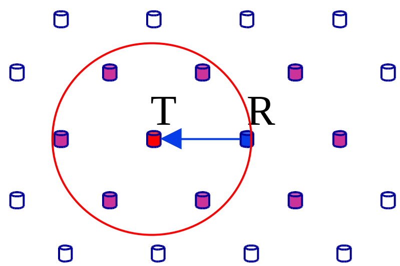
Data is sent



CTS - Neighbors of Receiver are silenced



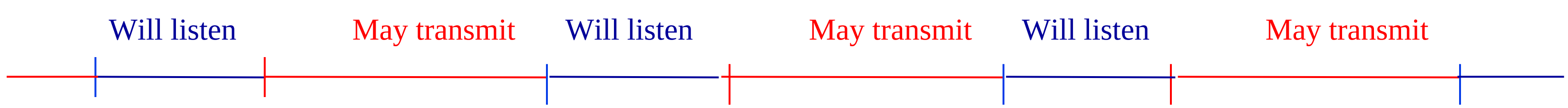
ACK is returned



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

Publishing schedules

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

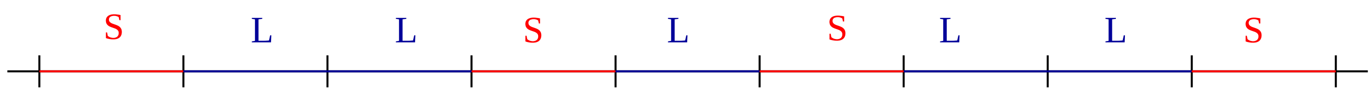


- Then other nodes can intelligently schedule their transmissions

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

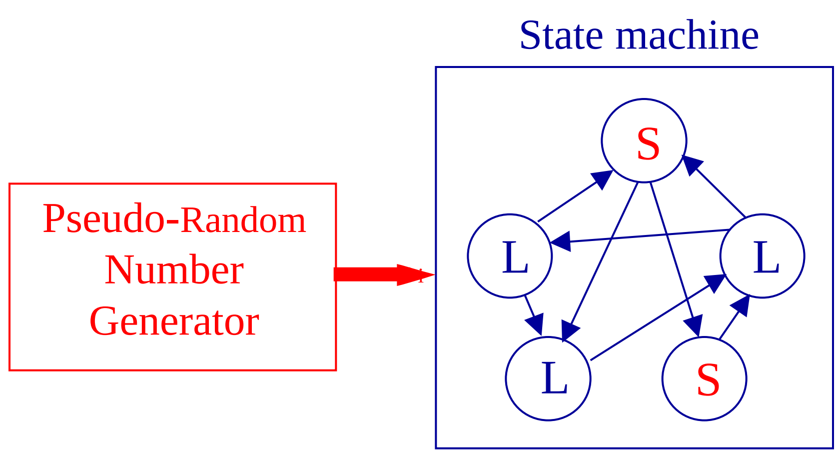
Random schedules

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



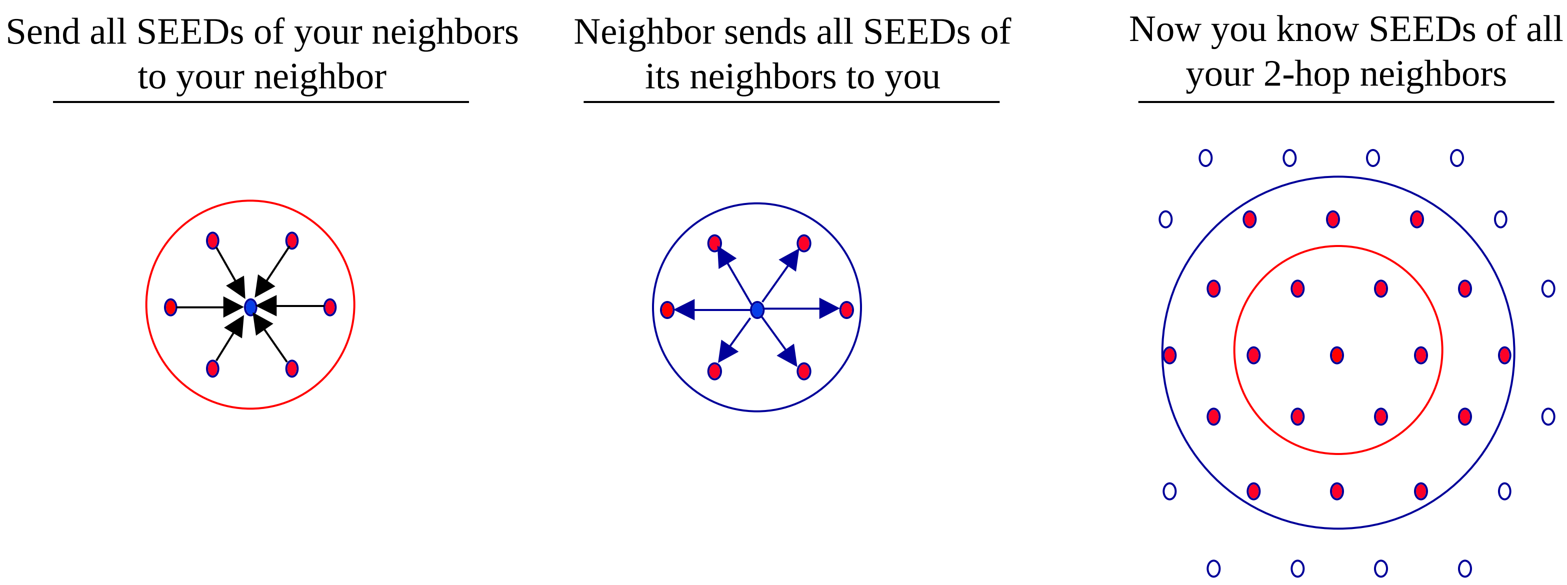
  - S = *Possibly* Transmit Packet
  - L = Listen for Packets

- Or more generally



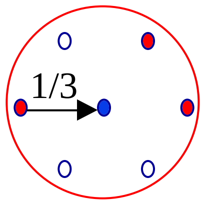
Publishing a schedule without publishing it: Exchanging SEEDs

- 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

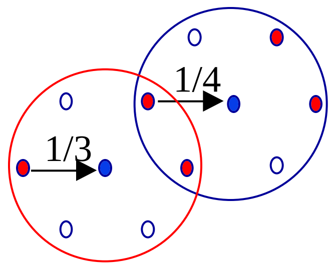


When should you transmit?

- 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



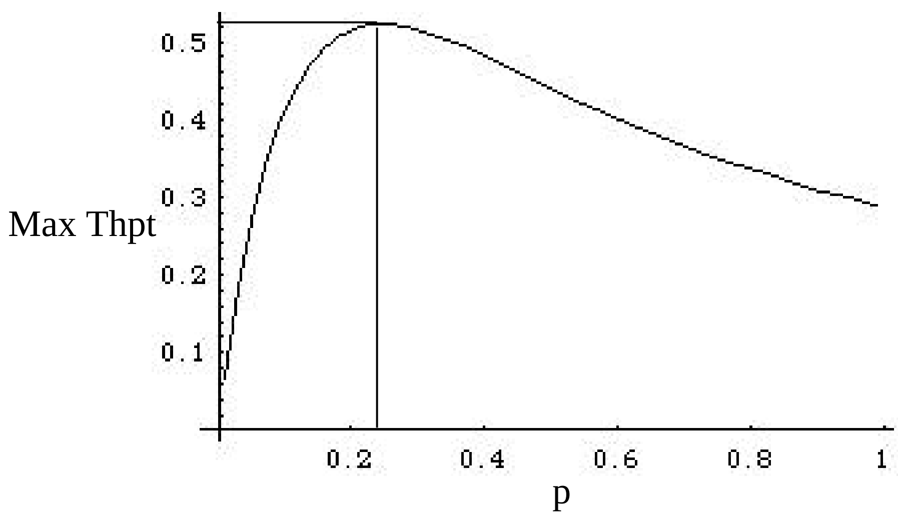
- Use $\frac{\alpha}{m+1}$ where $\alpha \approx 2.5$ in light traffic, $\alpha \approx 1.5$ in heavy traffic

Some calculations and simulations

- An approximate expression:

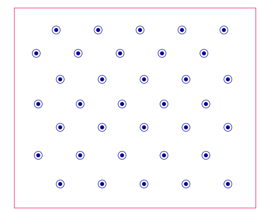
Max Thpt(p, α) = (N+1)*Throughput per Node

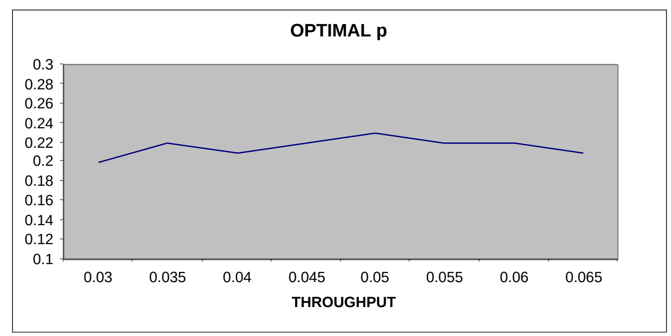
$$= (N+1)\pi_S \pi_L \sum_{m=0}^{N-1} \binom{N-1}{m} \pi_S^{\,m} \pi_L^{\,N-1-m} \frac{\alpha}{m+1}\left(1-\frac{\alpha}{m+1}\right)^m$$



Best p = 0.246
Max Thpt = 52.2%

- Simulation Results on 100 Node System:

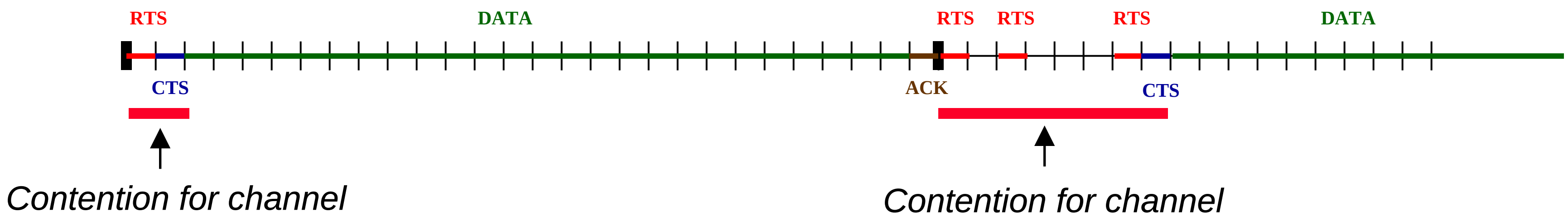




- $p \equiv$ 0.21 is a good choice fo all levels of demand
- $\alpha \approx$ 2.5 (light traffic)
  $\alpha \approx$ 1.5 (heavy traffic)

One more idea: Use SEEDEX only for reservation packets

- Use SEEDEX only for the RTS



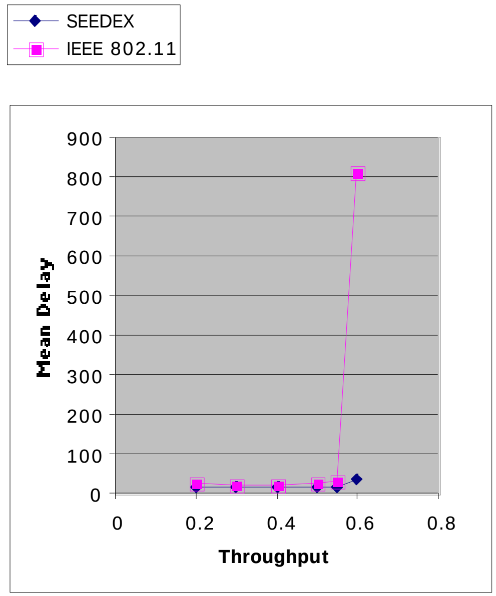
- Thus long DATA slots are not wasted

- The SEEDEX-R Protocol

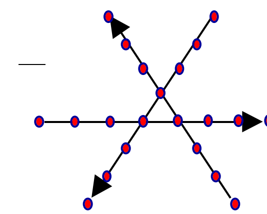
Comparison of SEEDEX and IEEE 802.11 on ns

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

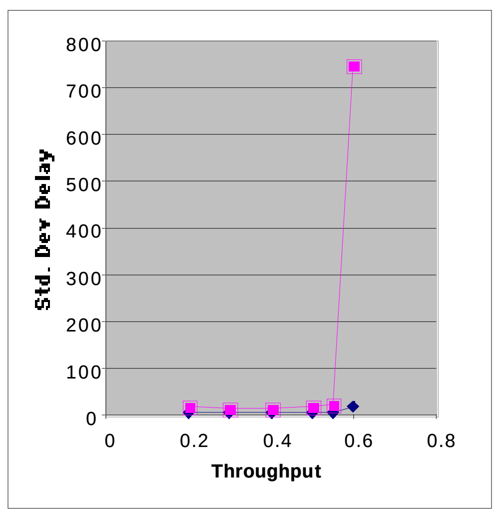


- Three contending flows

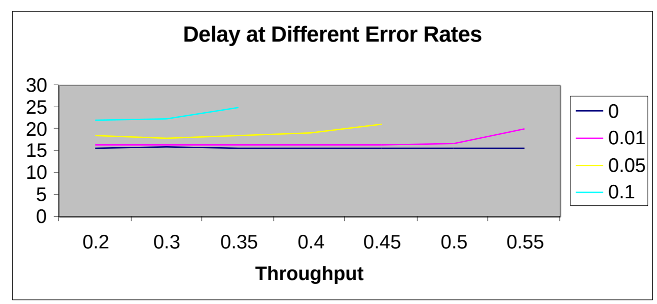


Std Dev of Delay

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



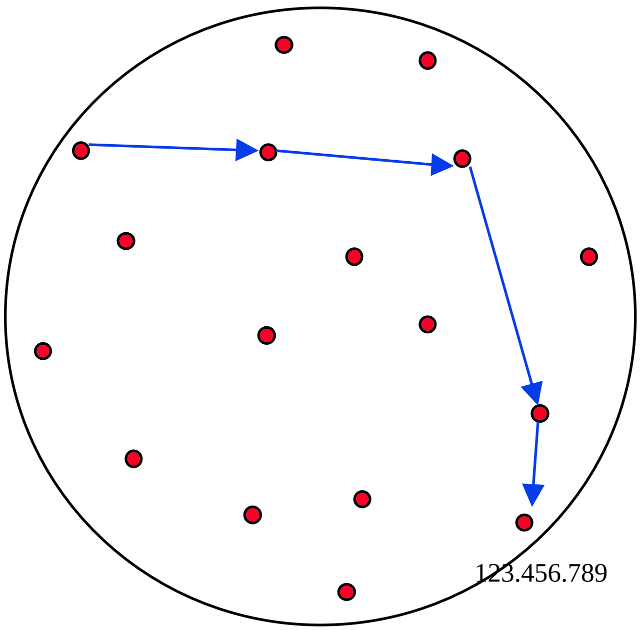
Mean Delay vs. Channel Error Rate



Protocol Design: Routing

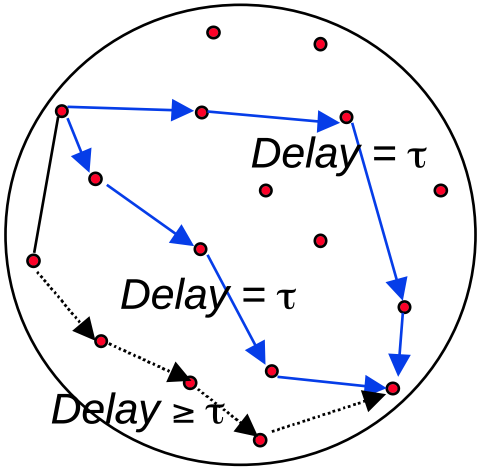
The Routing Problem

- How to find routes between sources and destinations of packets?
  - In wireless networks an IP address (such as 123.456.789) does not indicate its location
  - It does not tell us how to reach the destination
  - It is simply a SSN of a node



STARA: A System and Traffic Adaptive Routing Algorithm

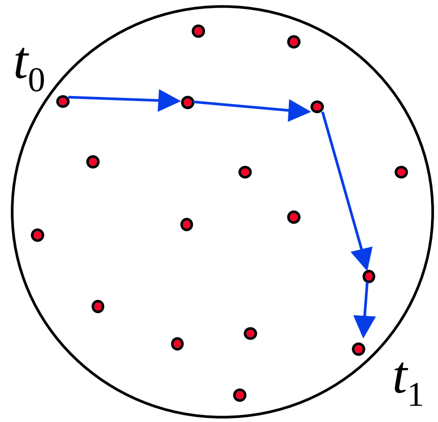
- Can we design an adaptive distributed asynchronous routing algorithm that adapts routes
  - To the topology of the network
  - To the prevailing traffic conditions?
- Goal: Route traffic from origin to destination such that
  - All utilized routes have the same mean delay
  - All unutilized routes have larger potential mean delay



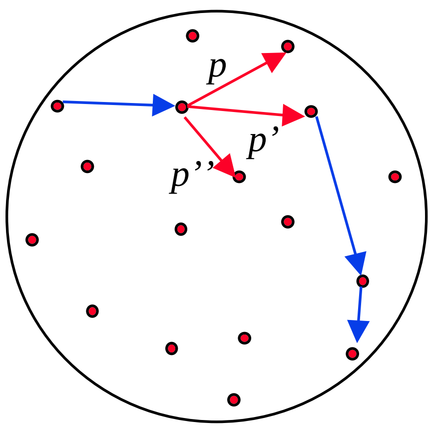
- Called the Wardrop equilibrium in transportation theory

Basic idea

- 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



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

Basic adaptation algorithms

- D_{ij}^{d} = Estimate of delay from i to d via j
- D_{i}^{d} = Estimate of mean delay from i to d over all routes
- p_{ij}^{d} = Proportion of traffic from i to d routed via j

- D_{ij}^{d}(new) = (1-λ) D_{ij}^{d}(old) + λ (Latest Observed D_{ij}^{d})
- D_{i}^{d} (new) =$\sum_j p_{ij}^{d}$(new) D_{ij}^{d}(new)
- 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!
- Ongoing work: Above algorithm with some modifications Cesaro equilibrates to a Wardrop solution

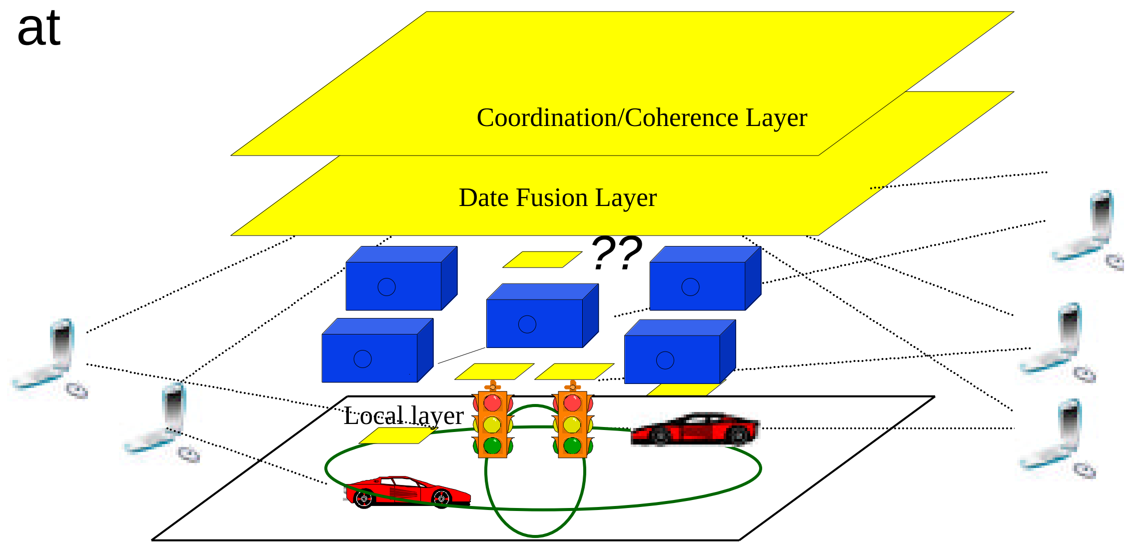
The architecture of convergence

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?

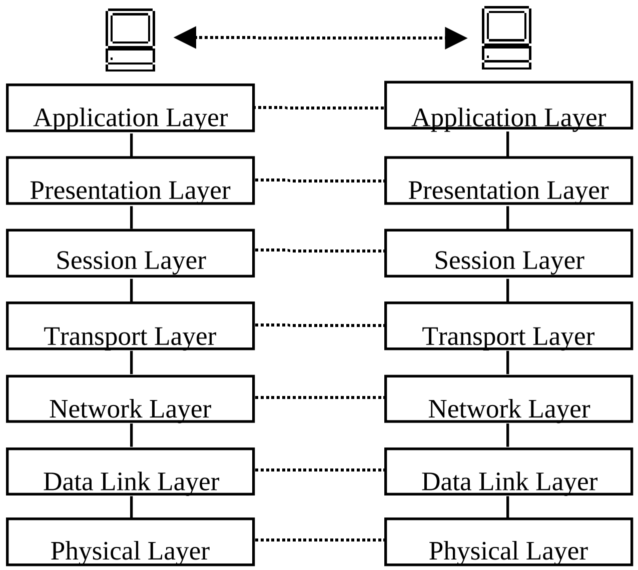
What are the right abstractions?

- 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?



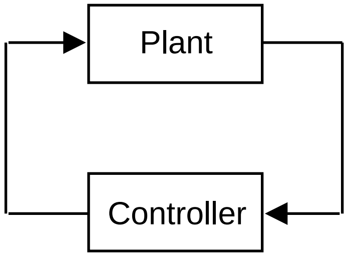
The importance of architecture

- 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

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- For hard copies send email to

  prkumar@uiuc.edu