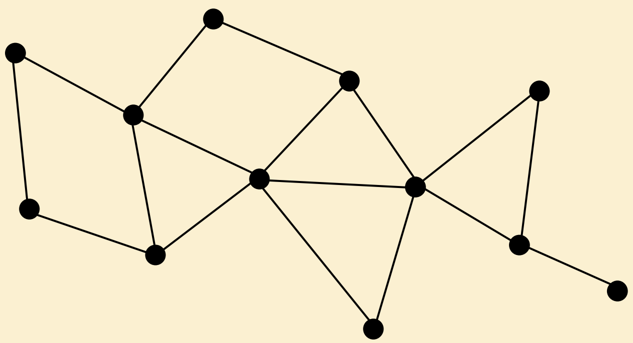
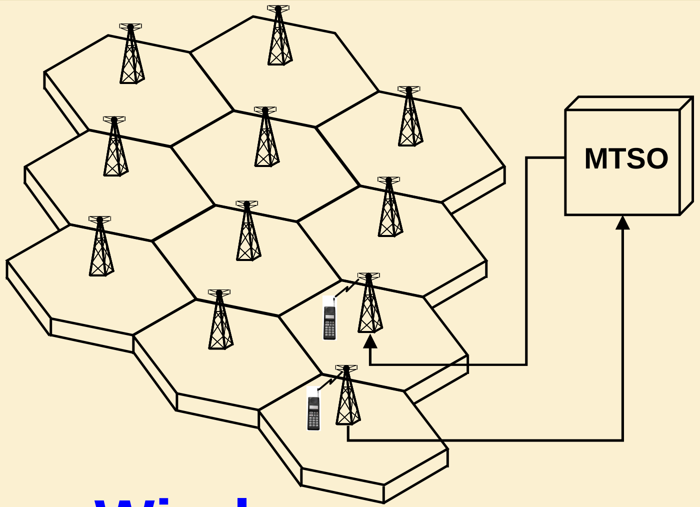
The Wireless Paradigm for Mobile Ad Hoc and Mesh Networking

John A. Stine

Successful networks



Wireline

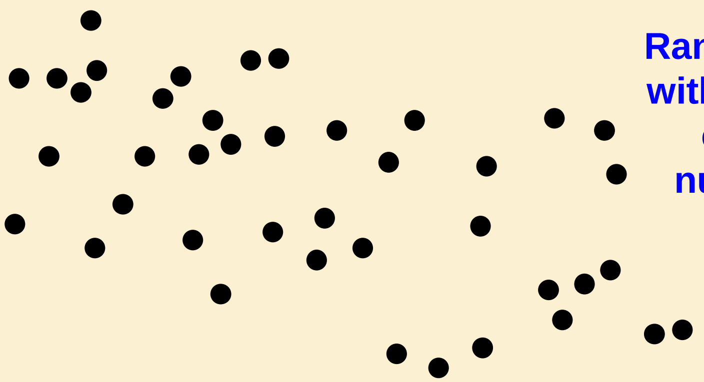


Wireless

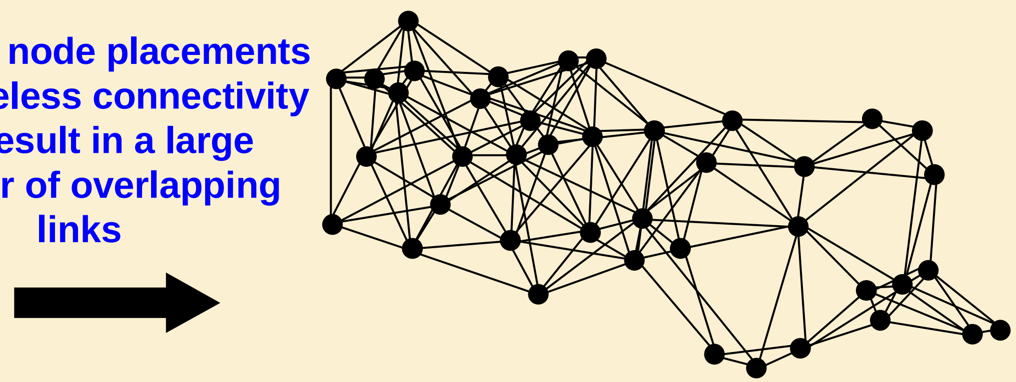
- Wireline networks provide the best example of what we want our ad hoc networks to do
- Wireless telephony systems provide the best example of the efficient use of RF spectrum
- The problem in wireless ad hoc networks is that their nature prevents us from taking advantage of the efficiencies of either
  - Varying topology prevents addressing and routing efficiencies
  - No central controlling nodes available to manage the RF channel

Current approaches

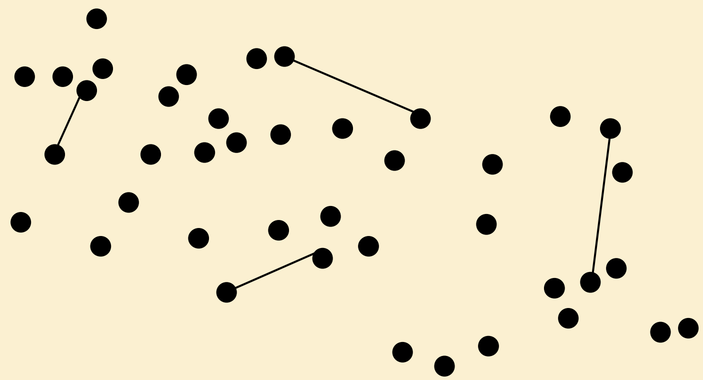
- Favor the wireline view
  - Access mechanisms attempt to create links
  - Routing protocols try to track links to understand topology



Random node placements with wireless connectivity can result in a large number of overlapping links



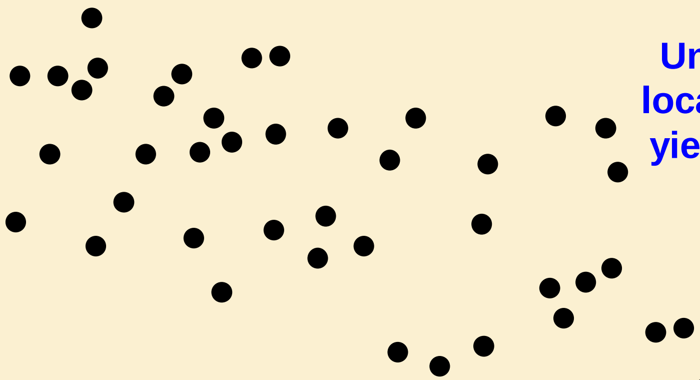
But in an instant only a small subset can be used



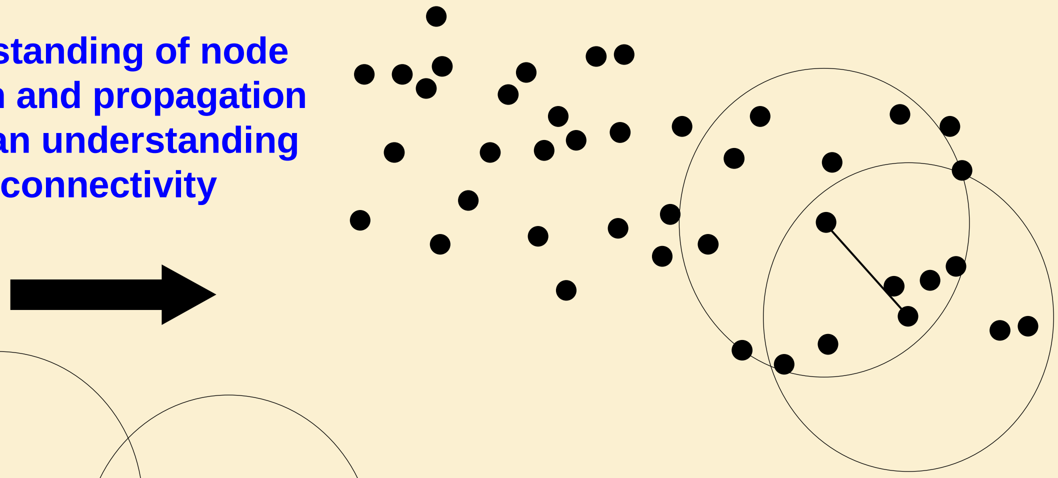
The link abstraction creates overhead and does not accurately represent the resource we want to manage

Our approach

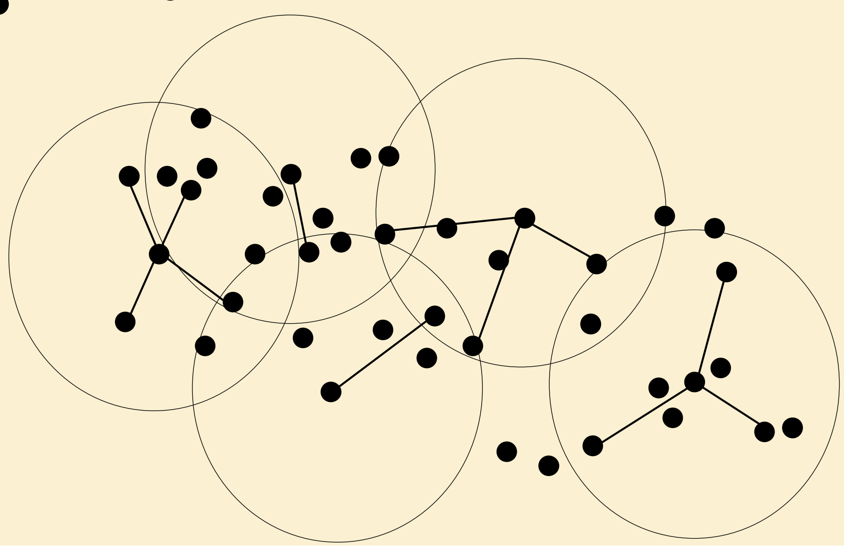
- Favors the wireless view
  - Access mechanisms attempt to create the cellular geometry which enables exploitation of cellular technologies
  - Routing protocols track nodes to understand topology



Understanding of node location and propagation yields an understanding of connectivity



Results in a greater density of links that can be used simultaneously



The mechanisms to create the network geometry and to track nodes are comparatively efficient and enable many benefits

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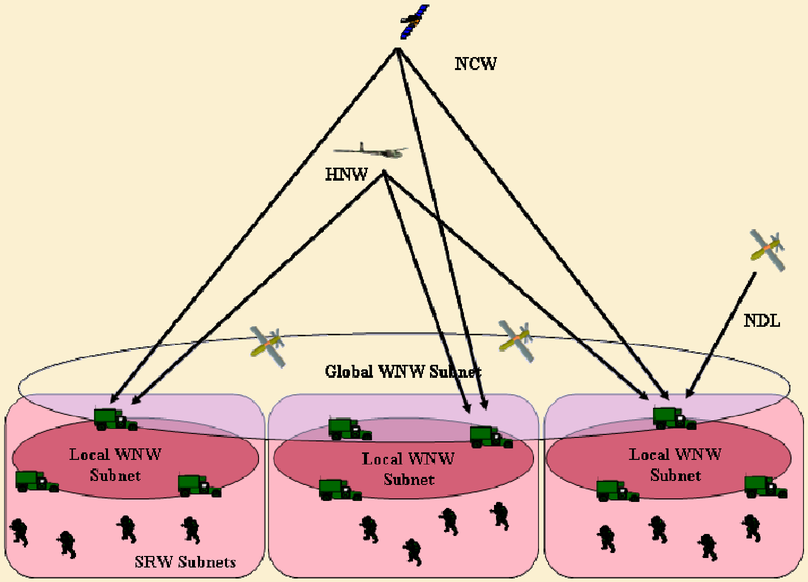
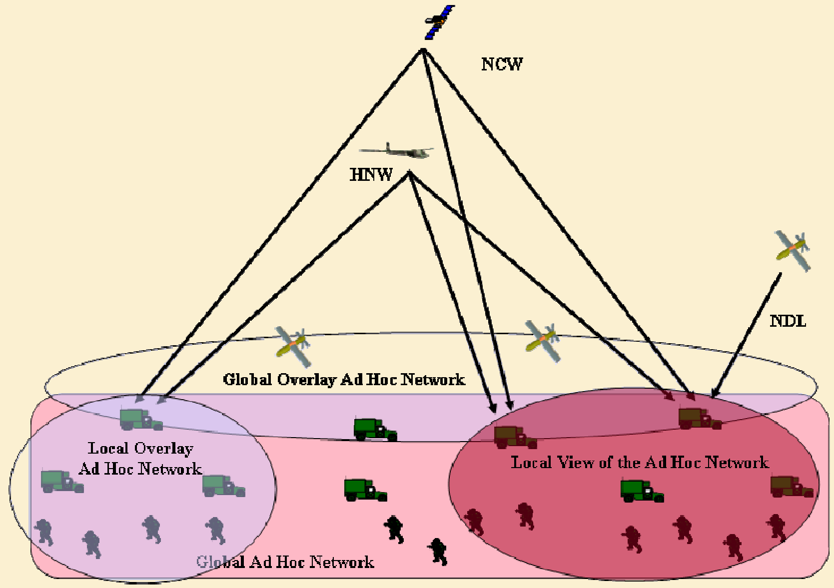
Differences in network architectures

Build the *last* tactical mile



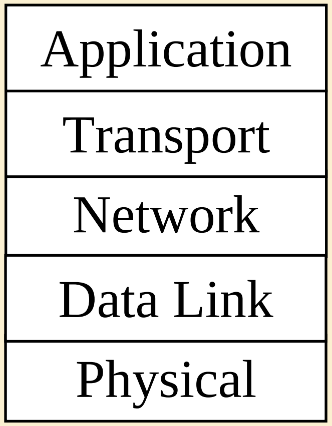
- Utility comes from being connected to the larger network
- A hierarchical architecture
  - Military organization is tethered to the network architecture limiting operational flexibility
  - Fails to allow local interoperability
  - Performance defies intuition

Build the *first* tactical mile



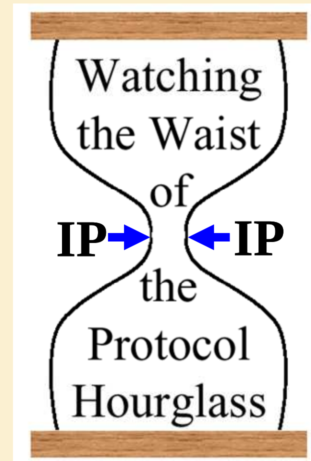
- Utility comes first from being connected to one's neighbors and then from being connected to the larger network
- A flat and hierarchical architecture
  - Any node can talk to any other node
- Use an overlay network to isolate traffic of a local community of interest

Interoperability vs. integration vs. performance



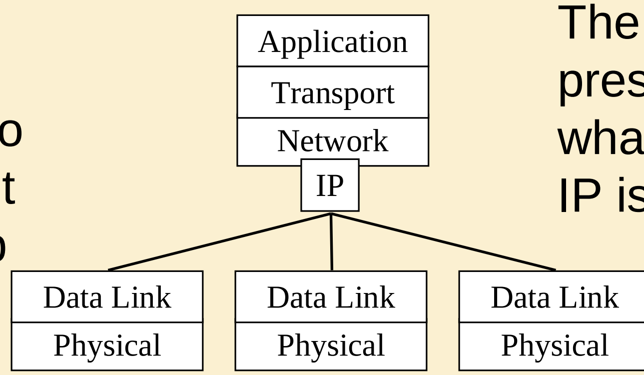
Interoperability is achieved through layering

If performance is an issue innovate and if integration is an issue standardize



Integration is achieved by standardizing a layer across protocol stacks

The decisions made at IP are which interface to transmit a packet and the next hop address to use



The typical presentation of what is beneath IP is a link

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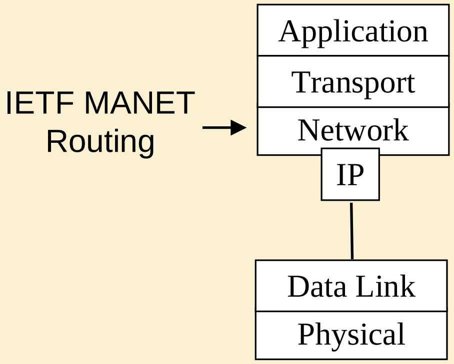
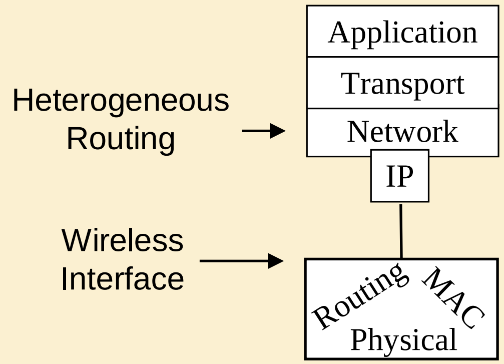
Differences in protocol stack

Perpetuating the wireline stack



Proposed wireless stack



- **The point of standardization is also the point of innovation**
  - **Most expensive place to innovate**
  - **Innovation necessarily stops pre-maturely**
- **Limited benefit**
  - **Wireline protocols do not work well in networks with volatile topology and unreliable connectivity**

- **Standardization creates a domain for innovation**
  - **IP is still the point of integration**
  - **Creating the ad hoc network is done by the device**
- **Benefits**
  - **Technology can be improved without the need to follow a standardization process**

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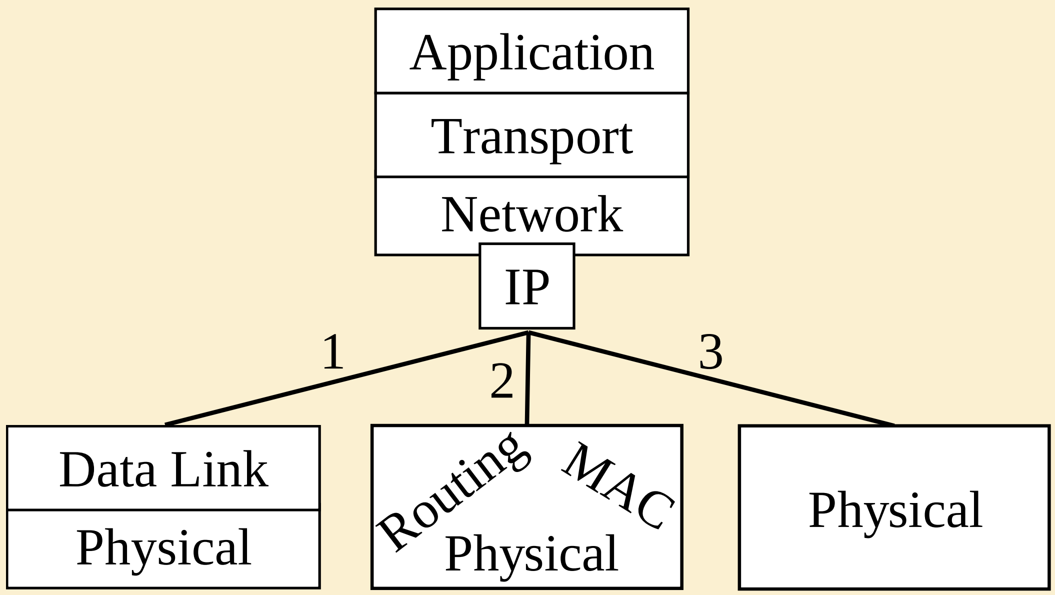
Heterogeneous node

- The interface we want to create for enabling our ad hoc network will also support the management of any spectrum using device
  - Provides a means for middleware or applications to query physical devices and to control them (At least their use of spectrum)



MAC Protocol Issues

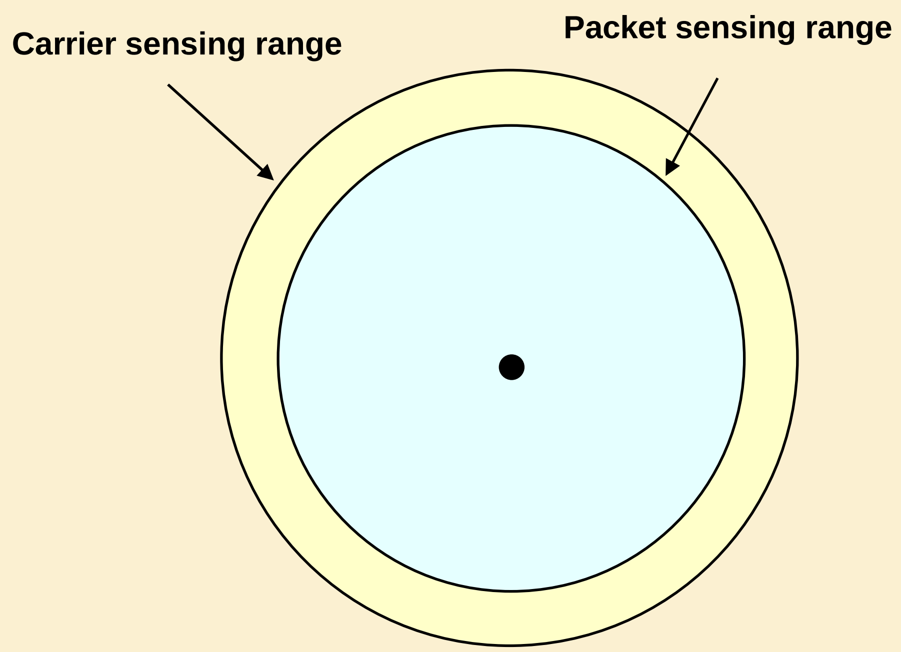
MAC protocol objectives

- Create the conditions that allows the physical layer to succeed
  - Prevent harmful interference
  - Insure access is fair
- Exploit the specific features of the physical layer to improve network capacity, reliability, and longevity
  - Channelization
  - Low energy state
  - Adaptation of
    - Power
    - Data rate
    - FEC rate
    - Antenna direction

In choosing a MAC protocol for a physical layer you must evaluate whether it can exploit the physical layer

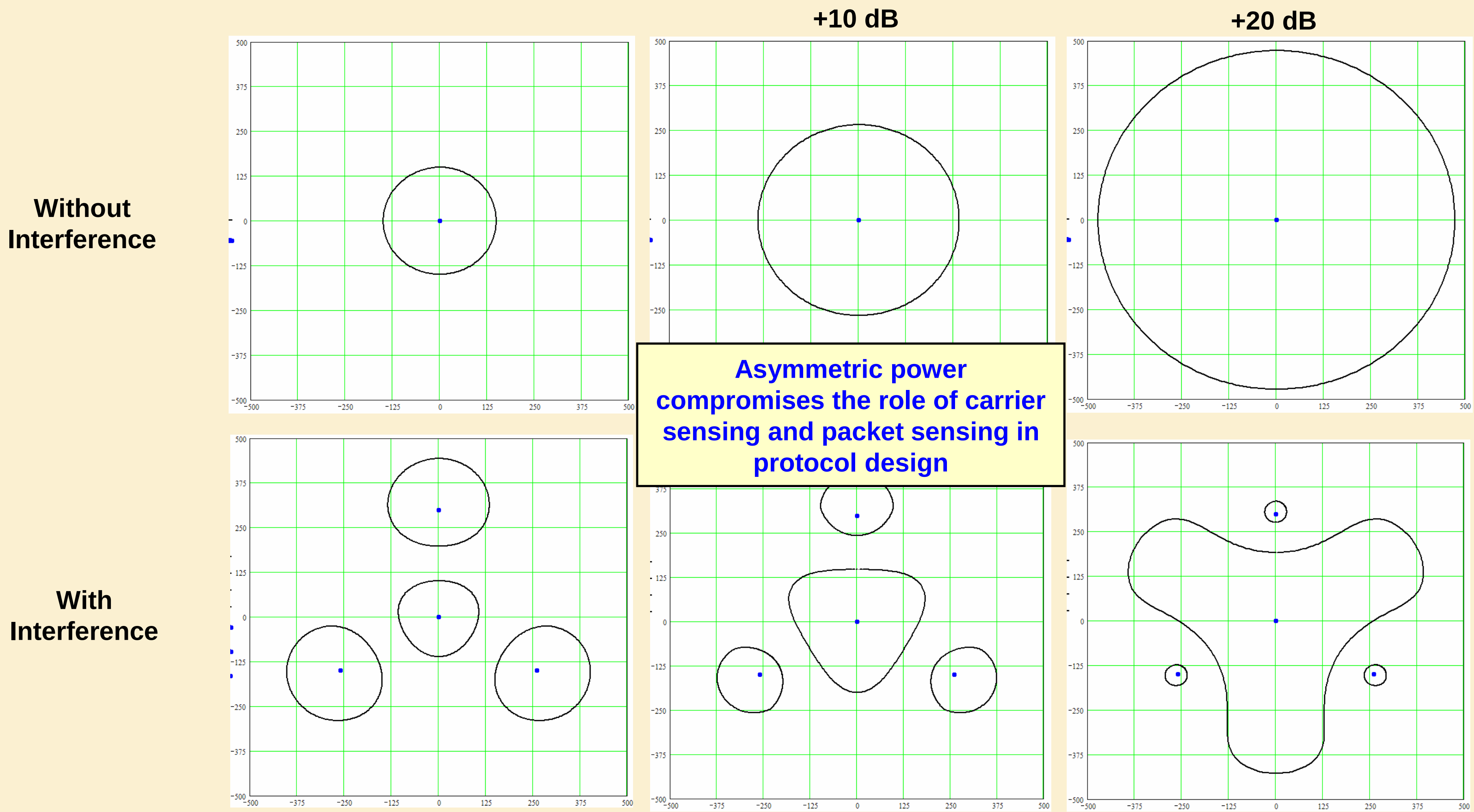
Critical mechanisms used in MACs

- Packet sensing range
  - The range from a transmitter that a receiver can capture a packet
  - Factors that affect packet sensing range
    - Packet size
    - Data rate/spectrum
    - Interference
- Carrier sensing range
  - The range from a transmitter that a receiver can detect a transmission
  - Factors that affect carrier sensing range
    - Detection threshold
    - Interference



The capacity of ad hoc networks is interference limited

Effects of interference
Transmitter power on packet sensing range (1)



- **Increasing transmit power of nodes independently may not increase range and may reduce the range of neighboring transmitters**

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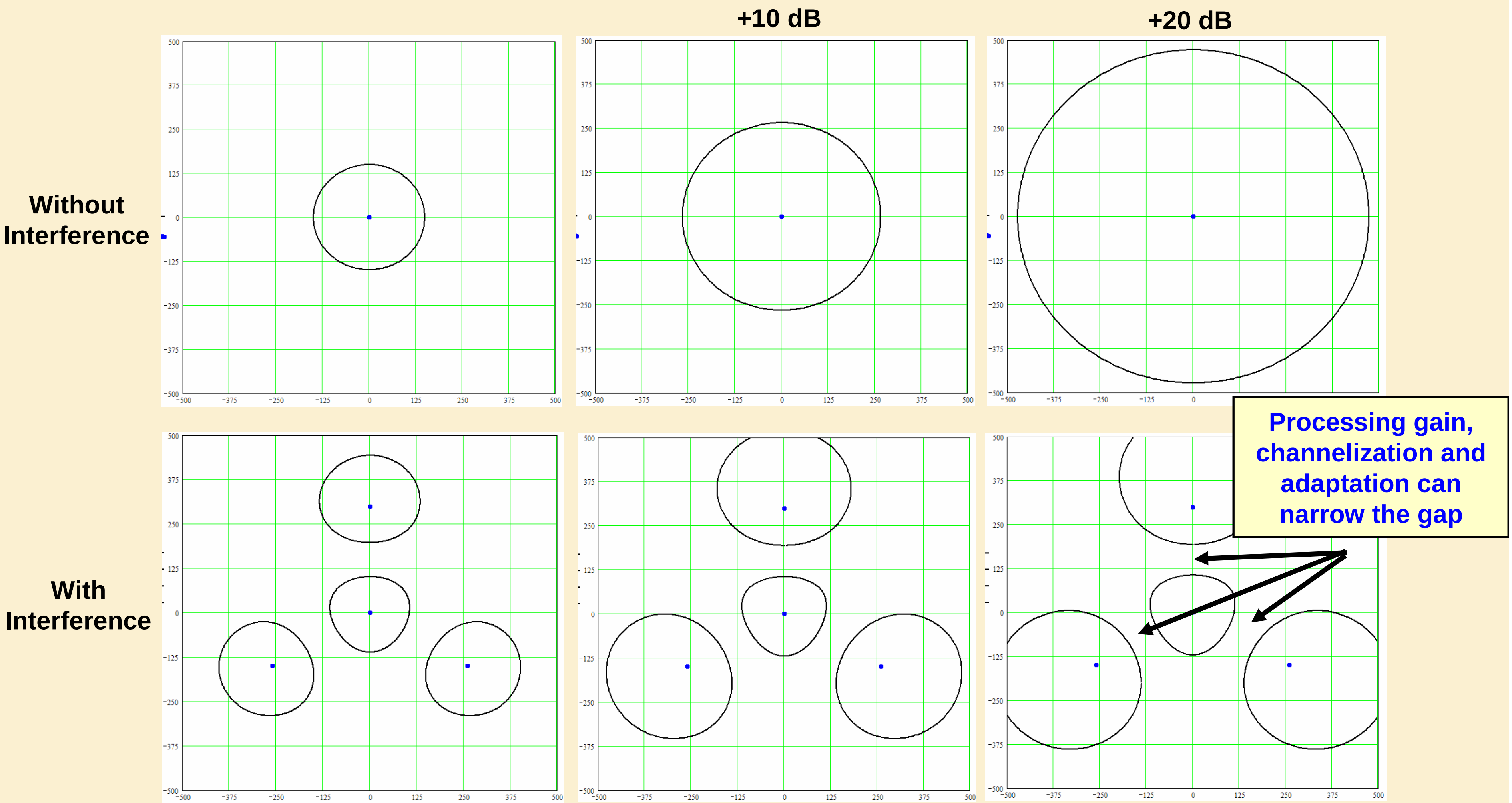
Effects of interference
Transmitter power on packet sensing range (2)



- Interference prevents range improvement in the direction of other transmitters even with increased power

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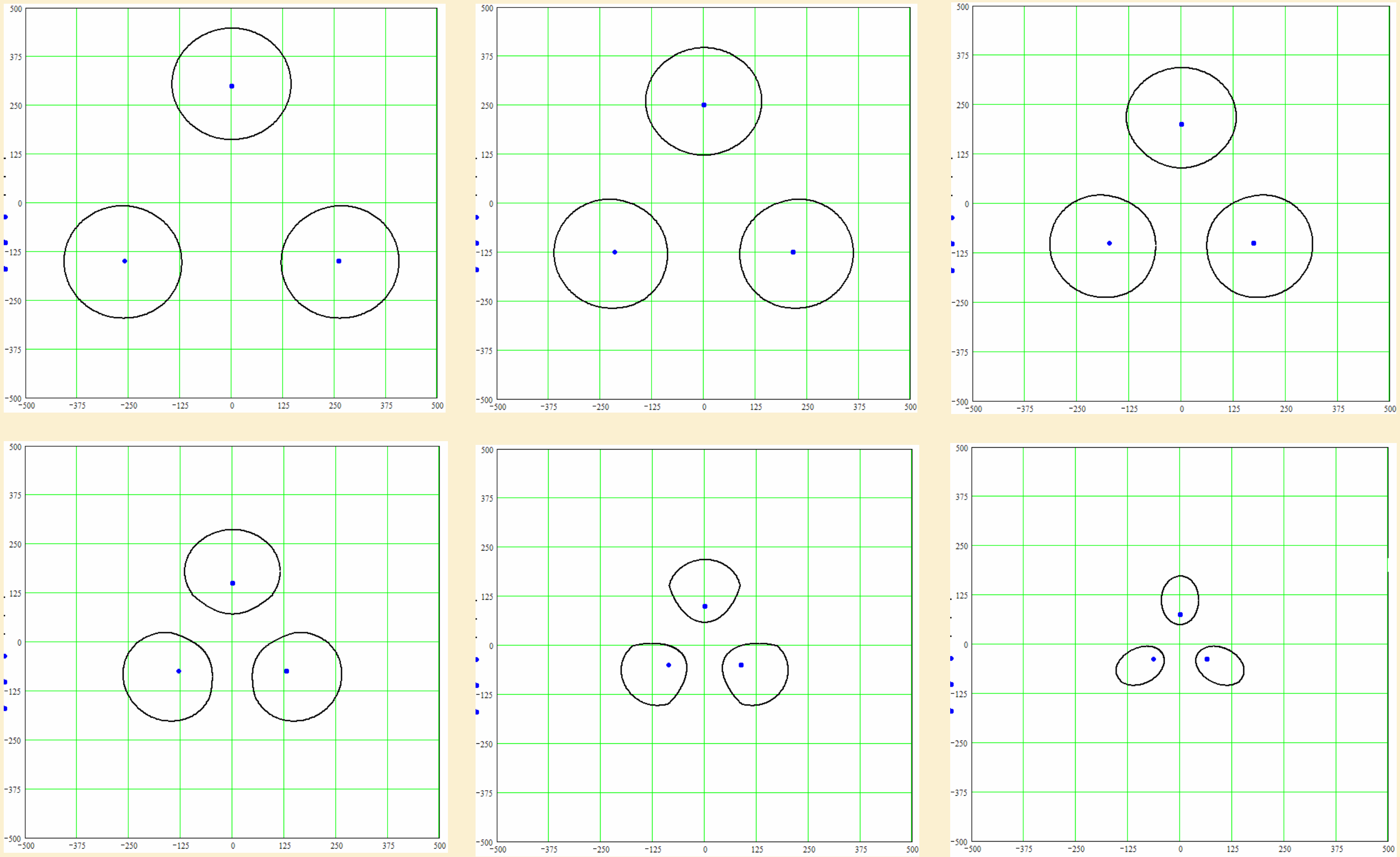
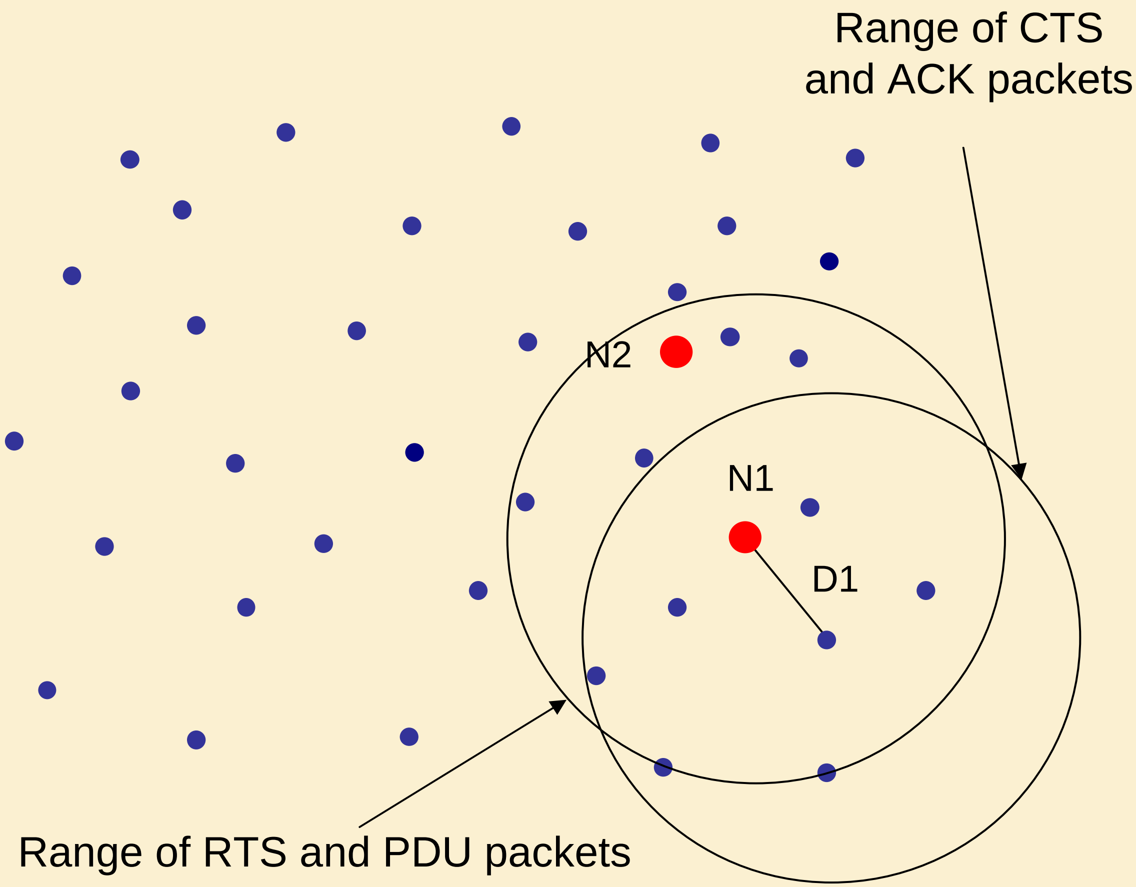
Effects of interference
Transmitter proximity on packet sensing range



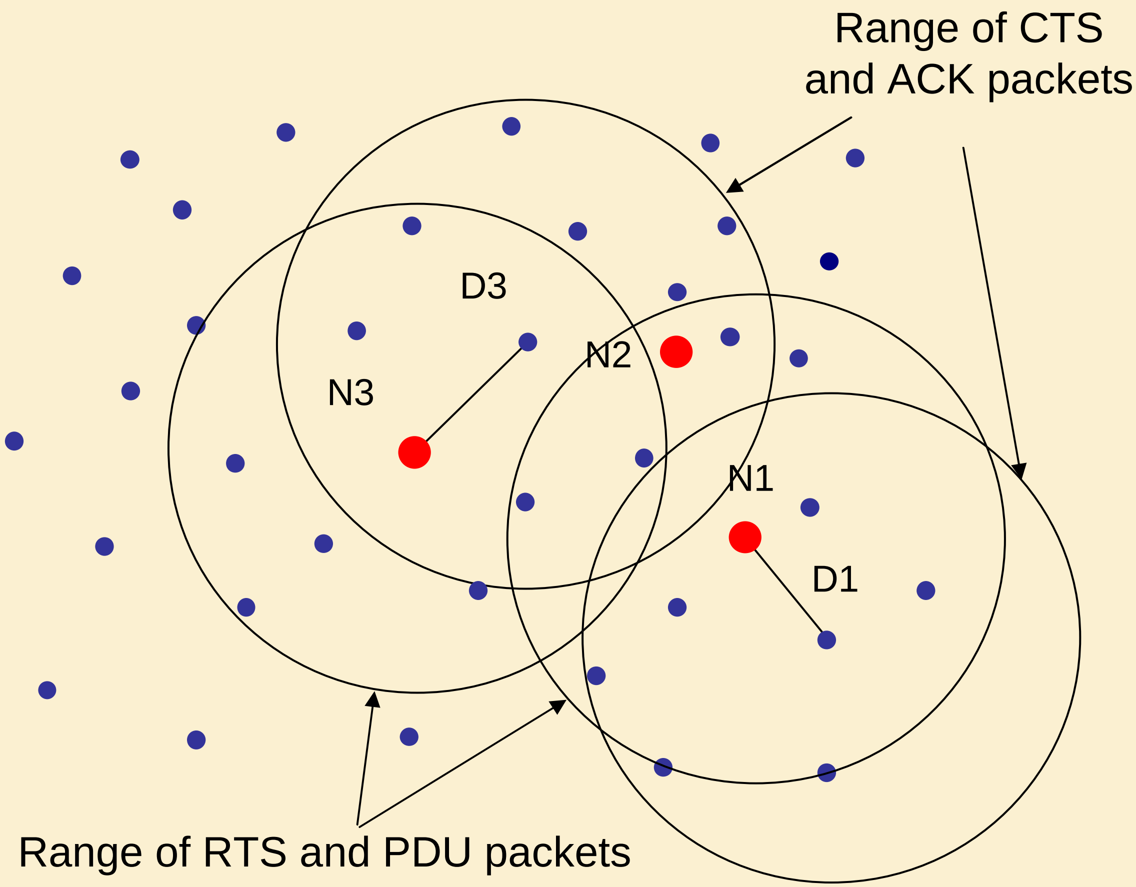
- Interference reduces the range of radios as the transmitters get closer together

Hidden terminals and unfair access (1)



- **N1 is sending a packet to D1 when N2 has a packet to send. N2 waits for N1 to finish**

Hidden terminals and unfair access (2)



- **Meanwhile, N3 begins transmitting a packet to D3. N2 does not hear D3's CTS transmission. A.k.a. Deafness problem**

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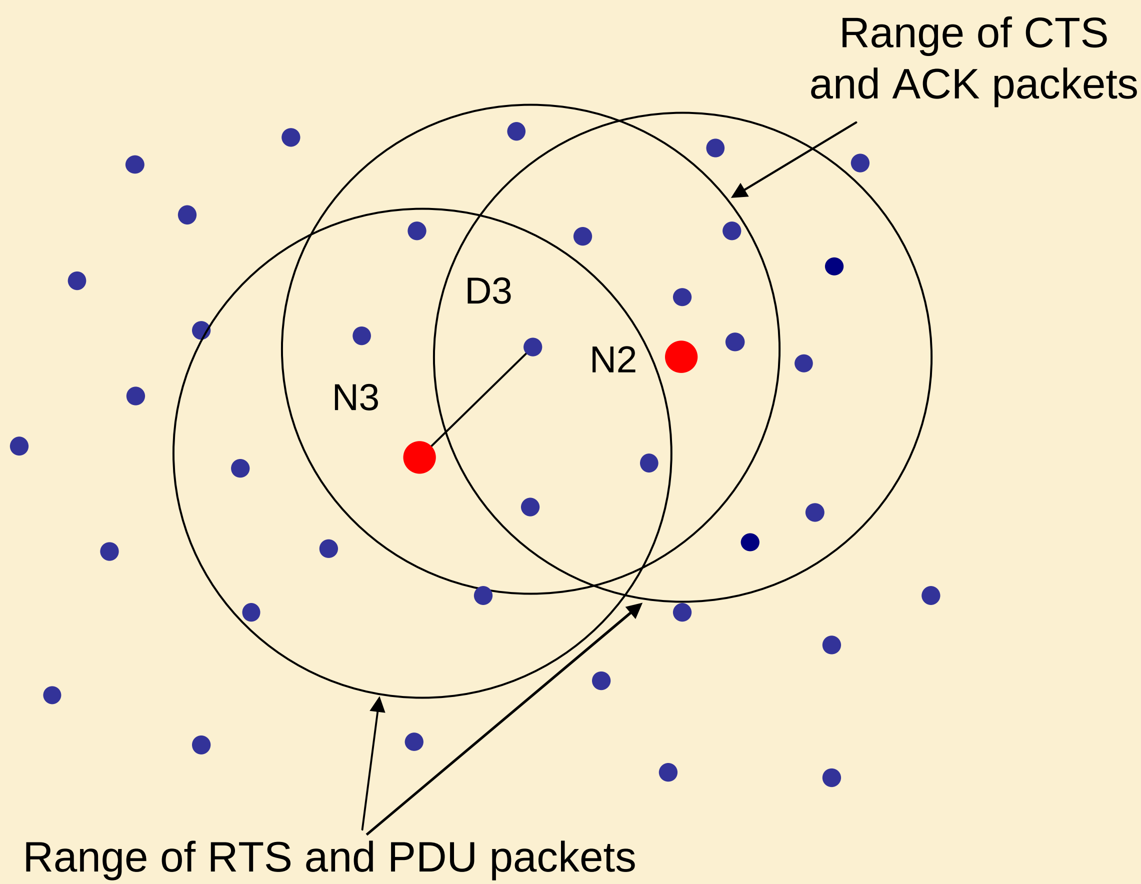
Hidden terminals and unfair access (3)



- **N1 and D1 complete there exchange so N2, which is unaware N3 is sending a packet to D3, sends an RTS interfering with the packet being received at D3. A.k.a. Hidden terminal problem**

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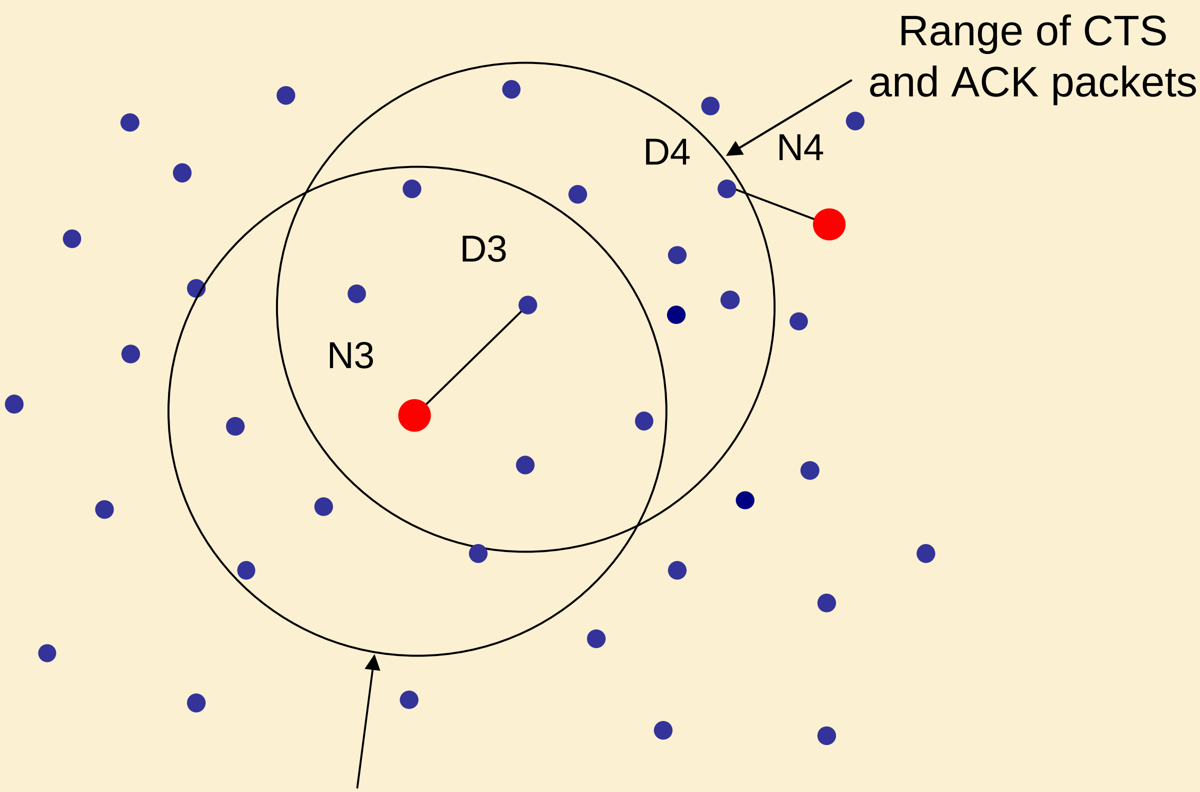
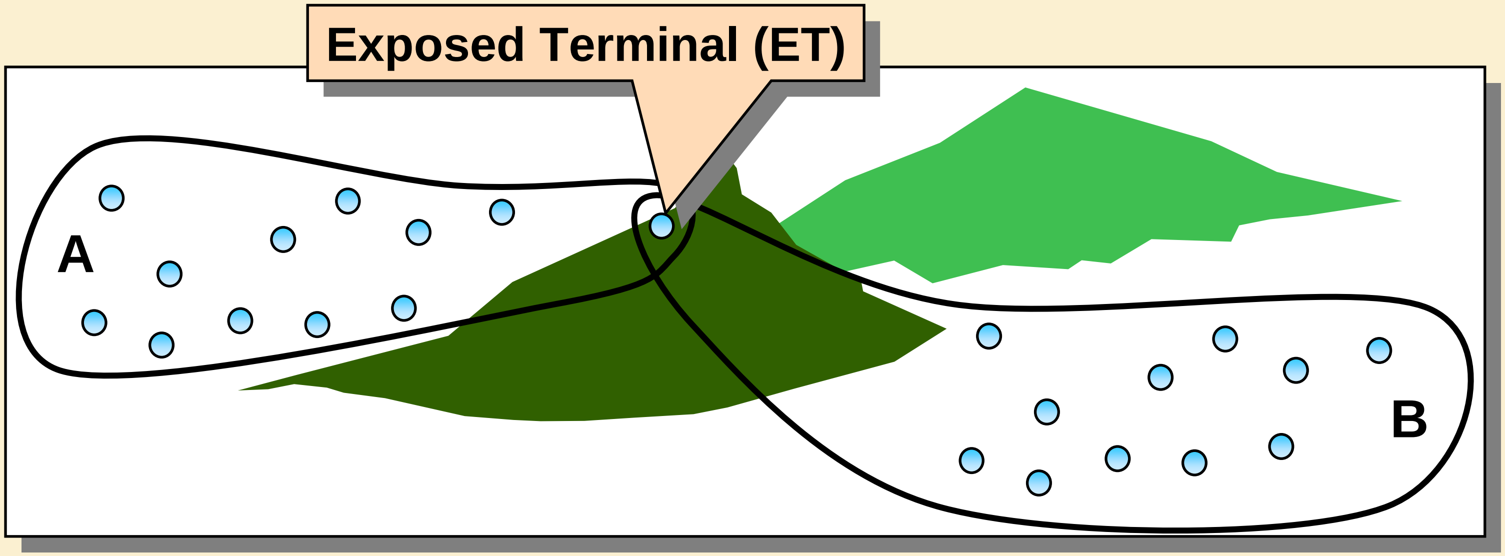
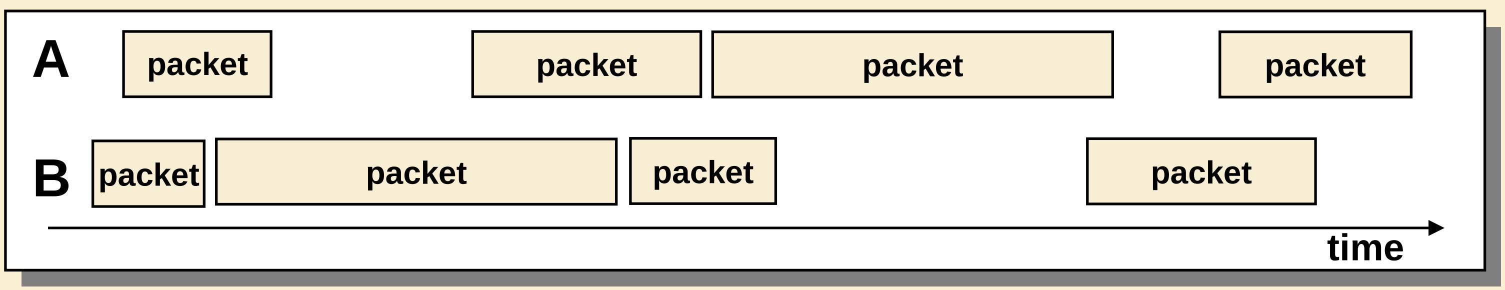
Hidden terminals and unfair access (4)



- **N4 wants to send a packet to D4 but D4 is deferring to the exchange between N3 and D3. D4 does not respond to N4's RTS's and so N4 backs-off and recontends. A.k.a. Muteness problem**
  - **When N3 and D3 are finished, if N4 has not already dropped the packet, N4 is at a disadvantage in gaining access compared to other nodes in range of D4. A.k.a Unfair access**

Exposed terminals (1)

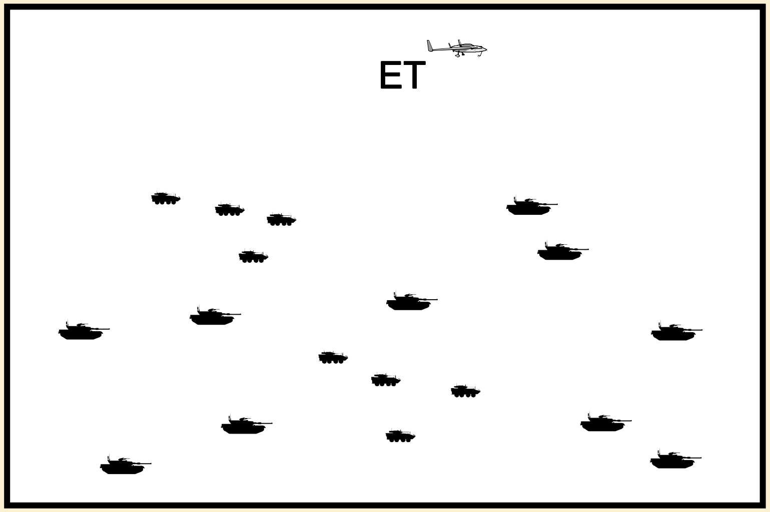




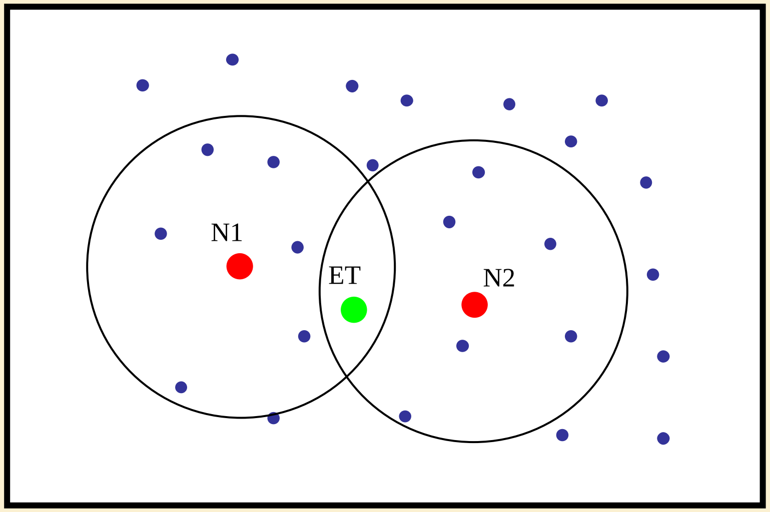
- **ET is a member of both network A and network B**
- **ET must wait for network A *and* network B to be quiet before it transmits**

Exposed terminals (2)

The UAV is in an advantaged position and is exposed to all the terminals on the ground.



N1 and N2 are information centers so are almost constantly receiving and transmitting traffic resulting in an exposed terminal.



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The role of adaptation

- **Adaption attempts to reduce the effects of interference and in the case of MIMO and smart antennas take advantage of the environment**
- **Depending on the adaptation method, receivers can be even more vulnerable to new interference after adaptation**

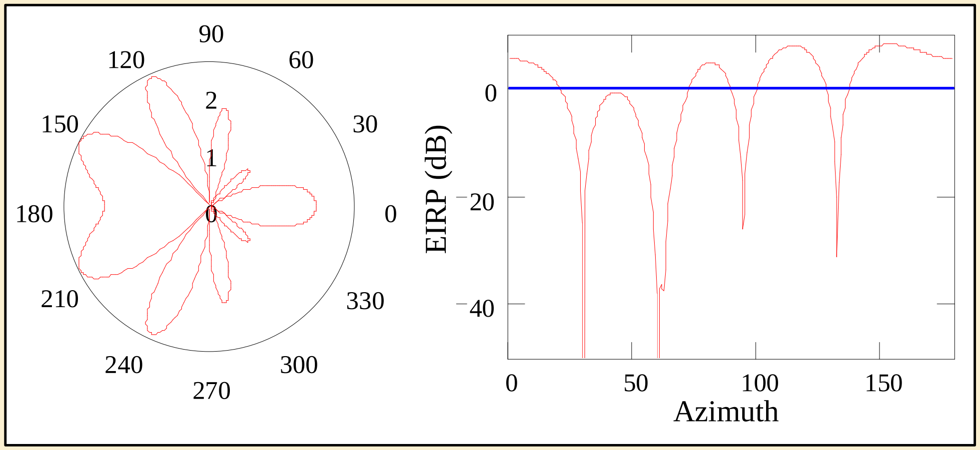
(n, d, θ, γ_1, γ_2,…)

n – number of elements

d – spacing between elements

θ – pointing direction

γ – null directions



Observations:

1) Narrow nulls,
2) Pointing direction on the side of a sidelobe
3) High gain in extraneous directions

Example adaptation for (8, .5, 100, 30, 60) normalized to 0 dB at 100°
using the Maximum SINR technique

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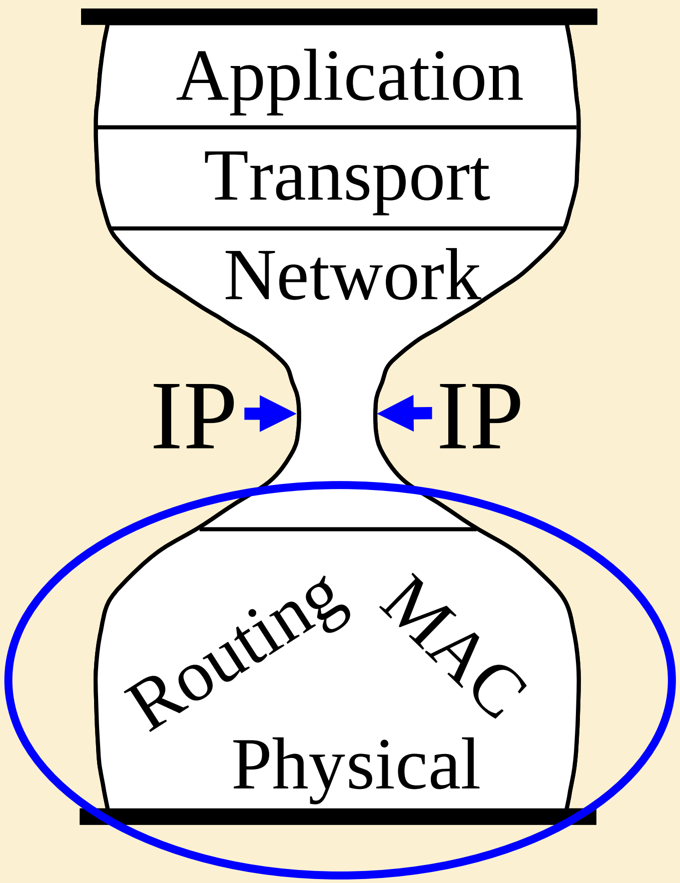
Our Solution Using the Wireless Paradigm

(Patent pending)



The ultimate benefit of changing paradigm are solutions to these problems in ad hoc networks

Protection from
- Hidden terminals
- Exposed terminals
- Congestion collapse
- Unfair access

Quality of Service
- Prioritized access
- Resource reservation
- Preemptive access

Routing
- Scalability
- Unified state dissemination
- Multimetric routing

Energy conservation
- Multiple dozing mechanisms
- Low energy routing

Physical layer adaptation
- Transmission power
- FEC
- Data rates
- Waveform

Capacity
- Orchestrated spatial reuse
- Channelization

Protocol Extension
- Multicasting
- Traffic engineering
- Network management
- Spectrum management

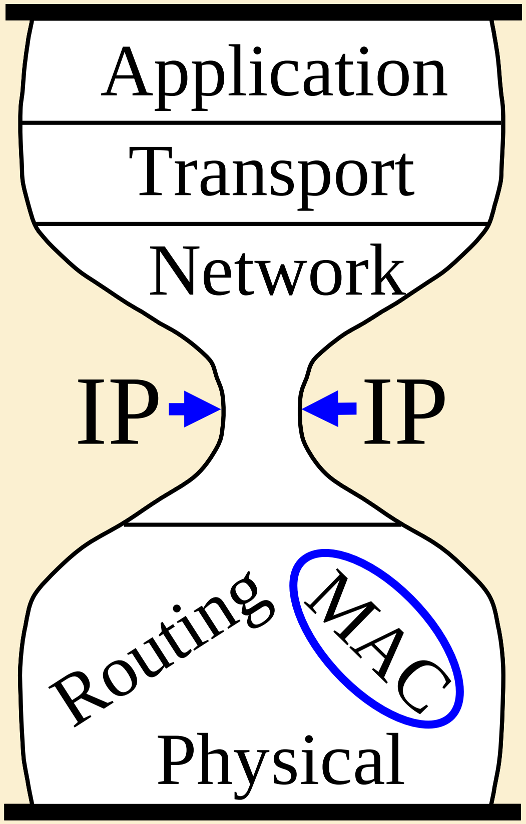
Technology exploitation
- Smart antennas
- CDMA/OCDMA
- MIMO
- Ultrawideband

Services
- Subscribing
- Service source identification

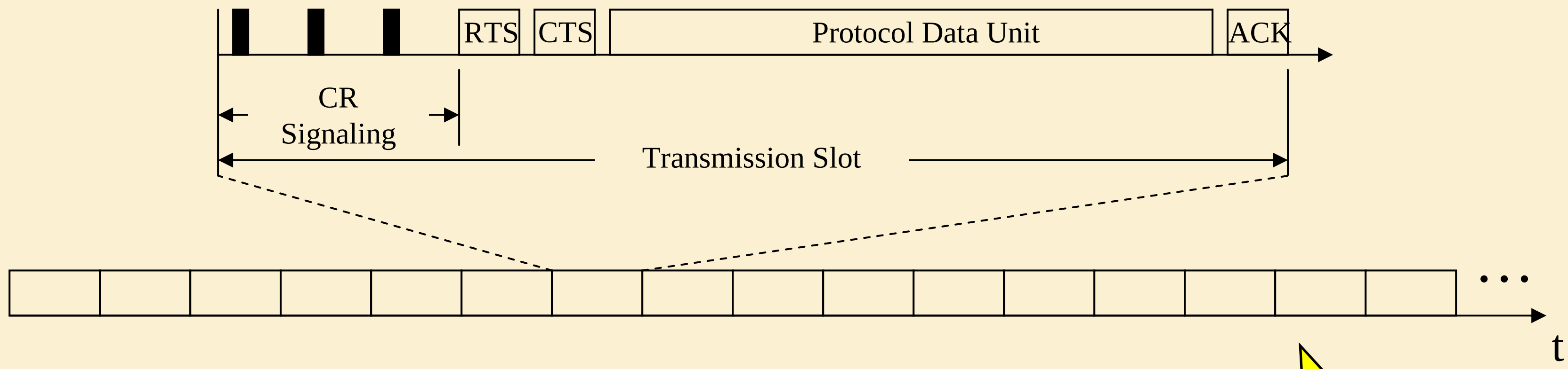
Security
- Restricted access
- Insider activity

Synchronous Collision Resolution (SCR)

(Patent pending)



Distinct characteristics of Synchronous Collision Resolution (SCR)



- Time-slotted channel
- Nodes with packets to send contend in every slot
- Signaling is used to arbitrate contentions
- Packet transmissions occur simultaneously

A paradigm not a specific design

Typically, other MAC protocols use time to arbitrate contention
(i.e. *network access delay or random slot selection*)

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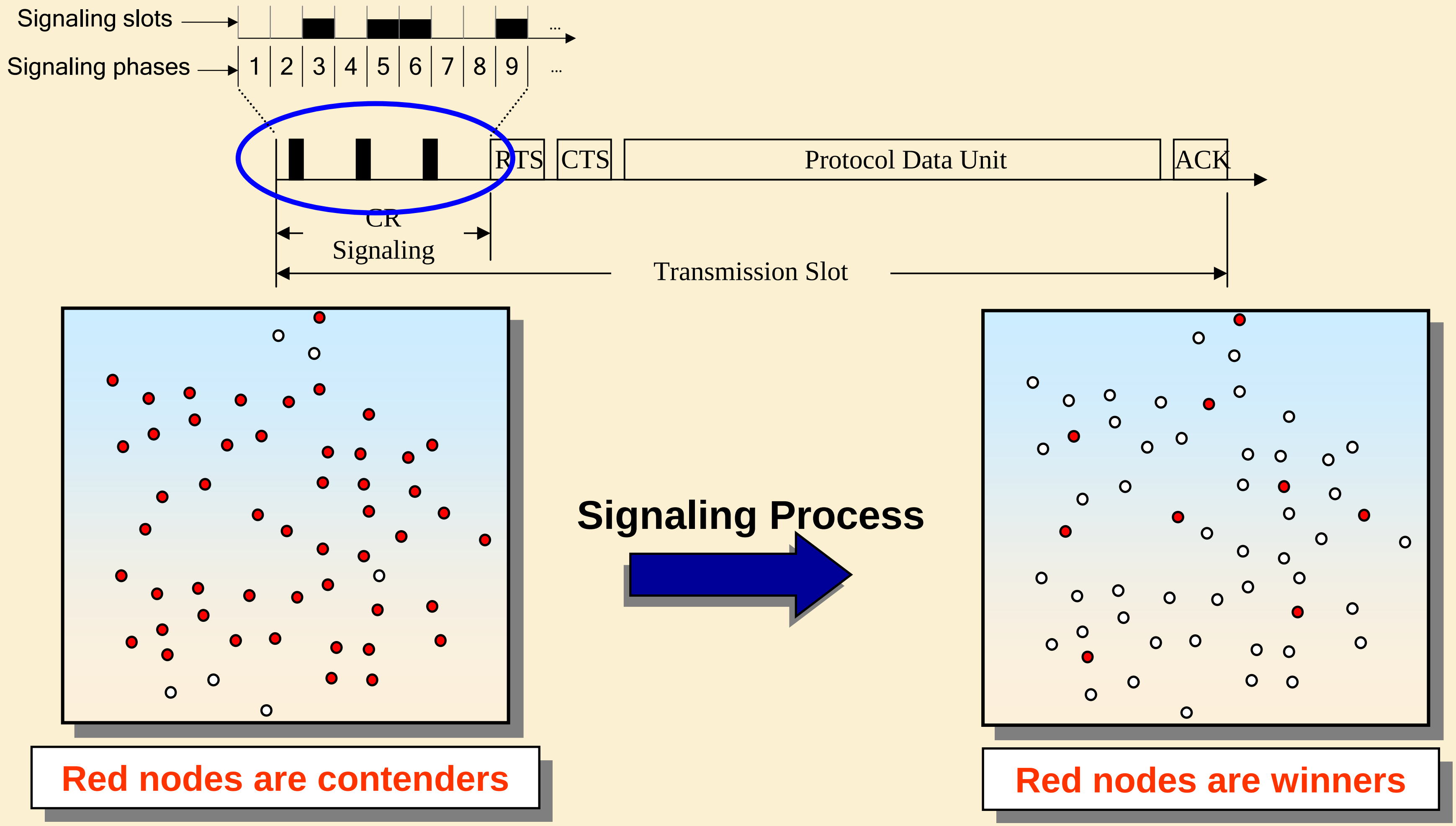
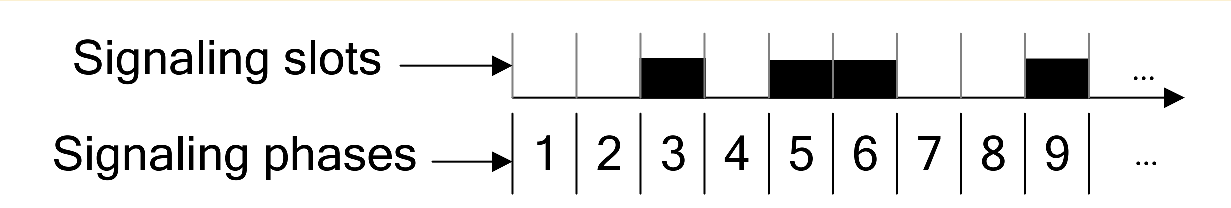
The purpose of Collision Resolution Signaling



- Prune the set of nodes that have a packet to transmit (i.e. "contenders") to a set of nodes which can transmit without colliding (i.e. "winners")

Rules of Collision Resolution Signaling (CRS)



- **Rules of single slot signaling**
  - **At the beginning of each signaling phase a contending node determines if it will signal. (The contending node will signal with the probability assigned to that phase.)**
  - **A contender survives a phase by signaling in a slot or by not signaling and not hearing another contender's signal. A contender that does not signal and hears another contender's signal loses the contention and defers from contending any further in that transmission slot.**
  - **Nodes that survive all phases win the contention**

DEMONSTRATION

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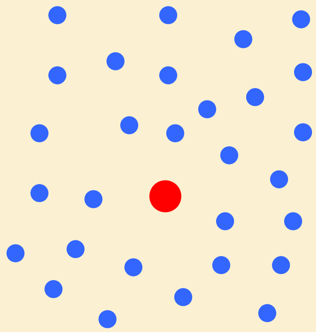
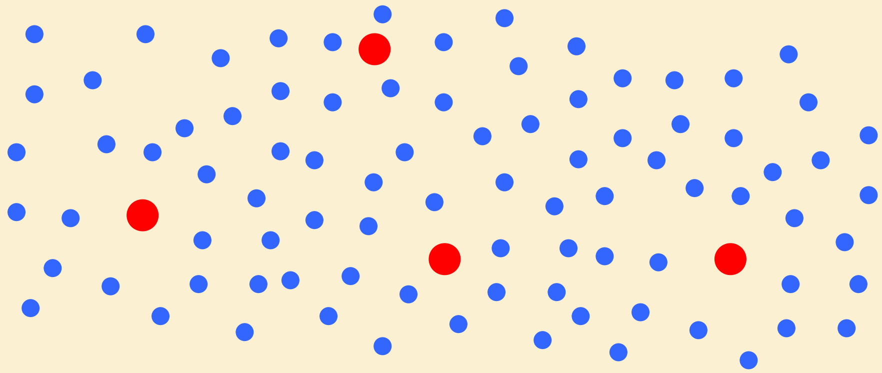
How effective is signaling?

- **Depends on how signaling is designed!**
- **Two ways to view signaling performance**



How well does it resolve contentions of nodes within range of each other (*ie. What is the probability that there is just one survivor?*)



How well does it distribute survivors (ie. *How far are survivors separated from each other? What is the density of survivors?*)

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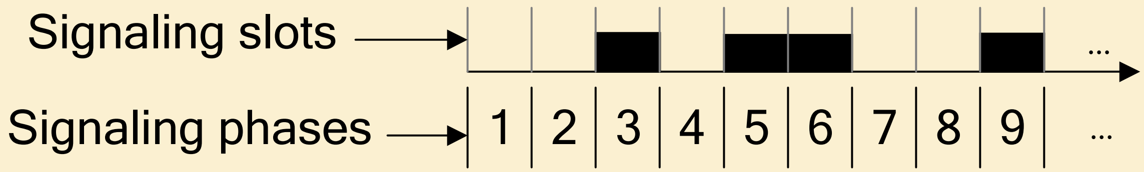
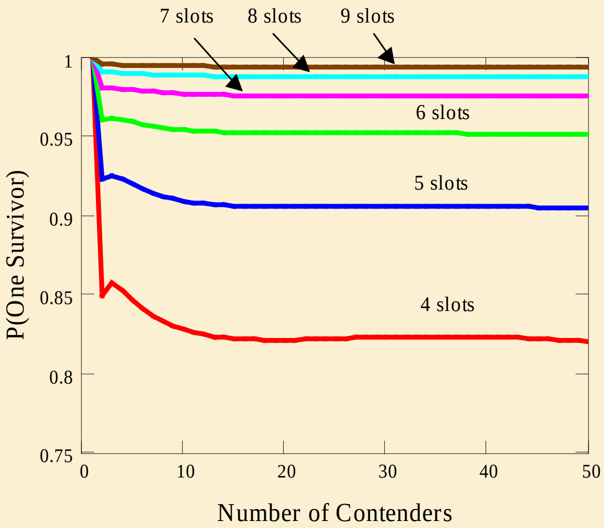
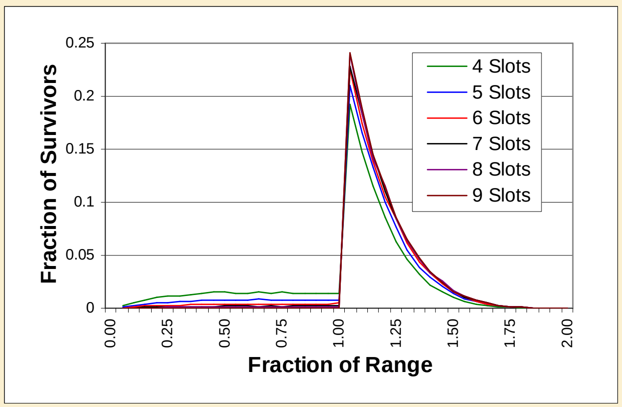
How well does signaling isolate just one survivor?



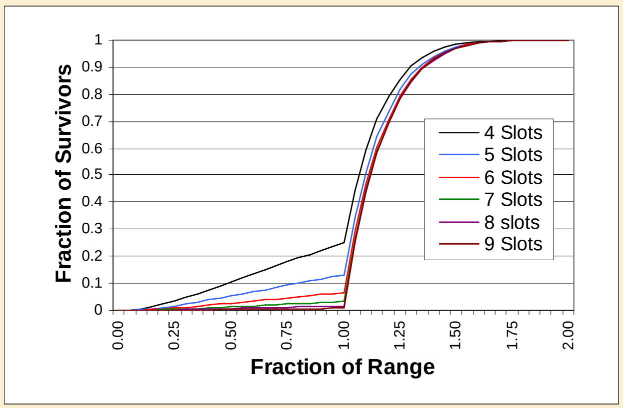
Resolving Contenders



Separating Survivors



Density of range to nearest surviving neighbor

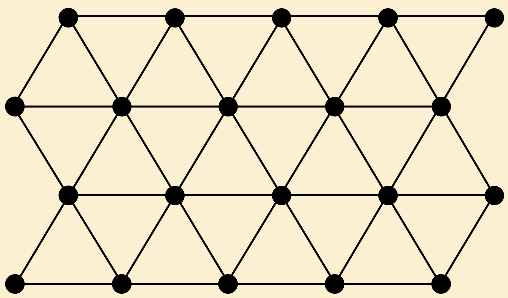


Cumulative distribution of range to the nearest surviving neighbor

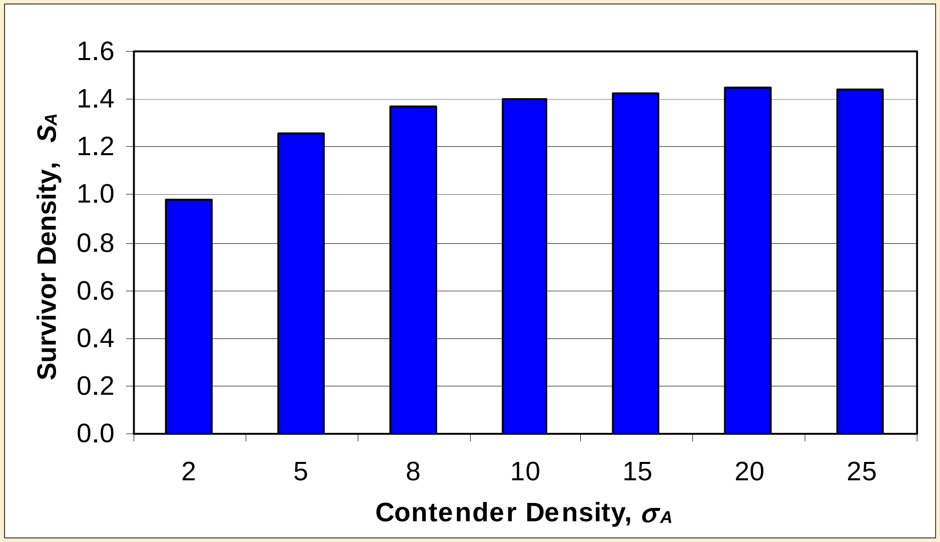
J. Stine, G. de Veciana, K. Grace, and R. Durst, "Orchestrating Spatial Reuse in Wireless Ad Hoc Networks using Synchronous Collision Resolution," *Journal of Interconnection Networks*, Vol. 3 No. 3 & 4, September and December 2002, pp. 167 – 195.

How dense are the survivors?

- **Answered through simulation**



Ideally $S_A = 3.63$



Simulation results with 9 phases

$S_A \cong 1.4$

S_A: Survivors per area (the number of transmitters per transmission area)

σ_A: Density of nodes (the number of nodes per transmission area)

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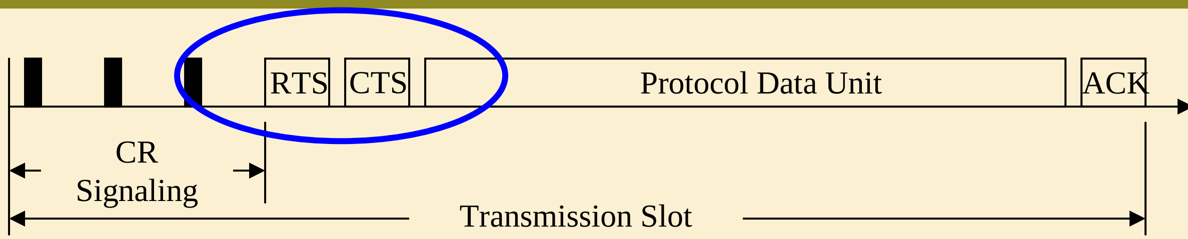
The request-to-send (RTS) clear-to-send (CTS) exchange



- The RTS-CTS exchange has two roles
  - Verify capture
  - Provide a feedback mechanism to optimize link performance
- Observations
  - All RTS transmissions occur simultaneously and all CTS transmissions occur simultaneously
  - Network interference is worst during these exchanges
  - Subsequent adjustments improve overall capture conditions
    - Dropped contenders
    - Lower transmission power
    - Optimized antennas

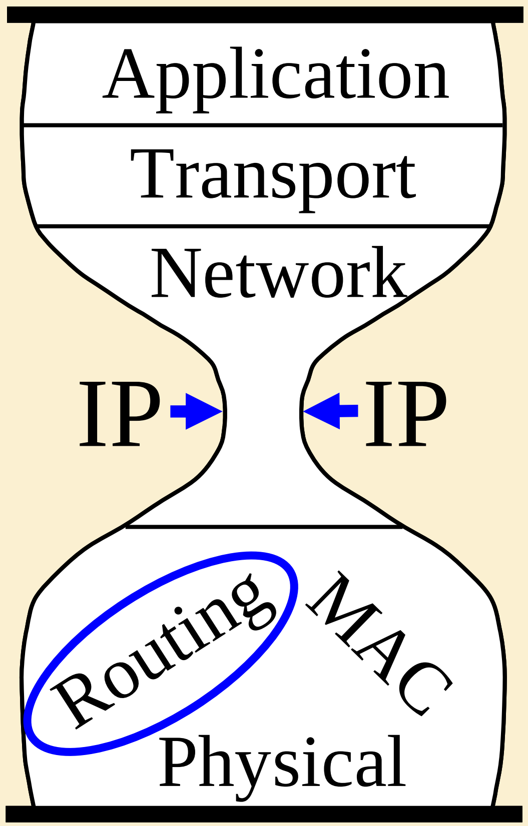
Additional SCR topics

- Signal design for contention resolution
- Breaking blocks using echoing
- Reactive echoing
- Priority Access
- Resource reservation
- Channelization
- Solving the near-far problem
- Energy conservation
- Smart antennas and MIMO

NSR Topics

Node State Routing (NSR)

Patent Pending



Routing protocol taxonomy (A new branch)

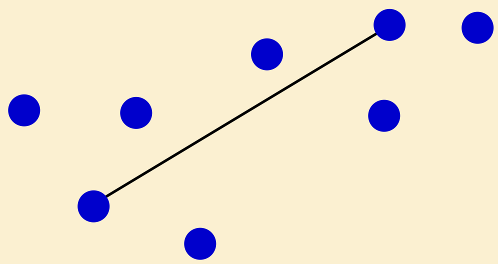
- Classical taxonomy
  - Distance vector (Belman-Ford)
  - Link state (Dijkstra)
  - Flood search
- Ad hoc network taxonomy
  - Reactive
  - Proactive
  - Hybrid
- Most MANET routing protocols are "link driven"
  - Use the discrete pairwise link abstraction
  - Links are discovered and their existence is disseminated
  - A collection of link information is used to understand topology
- Node state routing is not link driven
  - Nodes assess their own state in the network and this information is disseminated
  - Connectivity is inferred from the pairwise use of node states

Focus on how to calculate routes

Focus on how to best collect and disseminate network topology

Distinct characteristics of Node State Routing (NSR)

- **Necessary capabilities**
  - **Nodes have location awareness**
  - **Nodes can measure signal strength**
  - **Nodes can control transmission power**



- **Uses two constructs**
  - **Node – a point in space**
  - **Wormhole – two points in space with a directed link between them**
- **Node/wormhole states, as a minimum, identify the location of the node/end points and the measured rate of pathloss about the node/end points**
- **Topology is derived in three steps**
  - **All links between the constructs are inferred using pathloss and location information in the node states**
  - **A metric is assigned to the links**
  - **Dijkstra's algorithm is used to calculate routes**

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Node states

- **Physical layer states**

  1-meter path loss
  Propagation map
  Antenna gain map
  Location
  Velocity
  Direction
  Spectrum usage map
  Radio configuration

- **MAC states**

  MAC address
  Peer-to-peer channel
  Queue size
  CBR bitmap

- **IP states**

  IP addresses
  Network membership

- **Energy states***

  Energy reserve
  Dozing state
  Dozing offset
  Dozing period
  Receive fraction

- **Services**

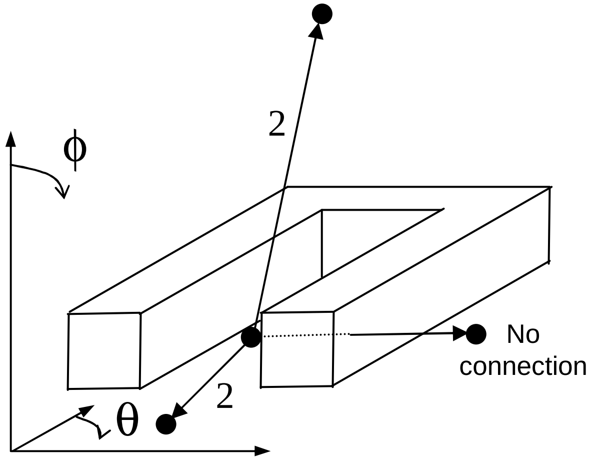
  Infrastructure status
  Service subscription

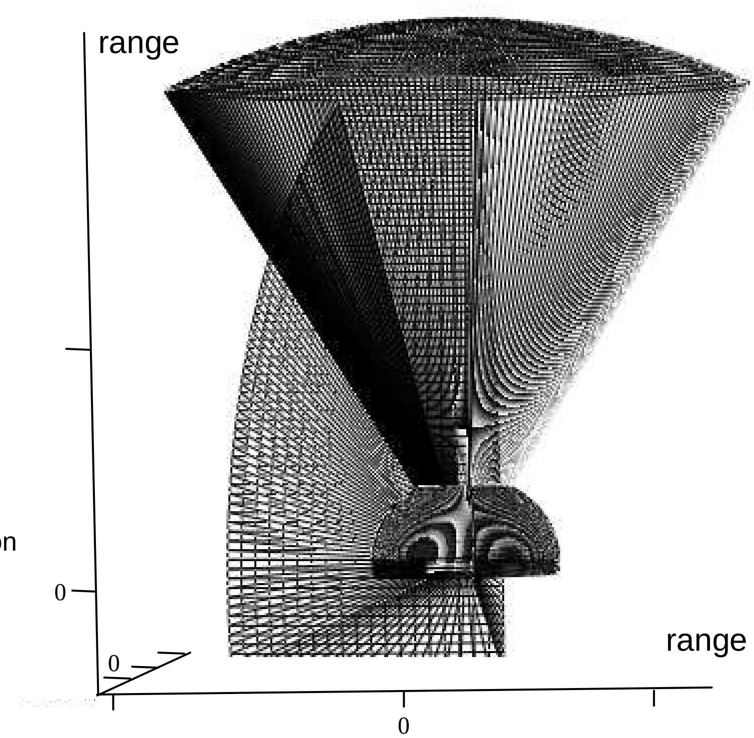
- **Administrative**

  Timestamp
  Cost to use the routing construct

*J.A. Stine and G. de Veciana, "A comprehensive energy conservation solution for mobile ad hoc networks," *IEEE Int. Communications Conf.*, 2002, pp. 3341 - 3345

Example propagation map





Propagation map → (2, 255, 30, 2.5, 120, 2, 140, 2.5, 255, 100, 7, 0)

Data structure that captures propagation in an urban draw

Overhead comparison

- Say the nodes in a 1000 node network have ten neighbors on average

	Link Driven	NSR
Tracked Entities	10,000 directed links	1000 node states
Effect of a Node Moving	Requires all previously connected nodes to transmit link state updates	1 node state changes requiring 1 node state update

- Node state dissemination is the sole state dissemination mechanism in the ad hoc network and supports all administrative functions (e.g. QoS, network management, multicasting, spectrum management, potentially even blue force tracking)
- Link driven protocols only support routing and usually require additional protocols and state dissemination mechanisms for a full networking solution (e.g. determining channelized neighborhoods, QoS, multicasting, network management)

Additional NSR topics

- Predicting connectivity and propagation maps
- Advantages over wireline approaches
- Scaling
- Quality of service
- Multicasting
- Spectrum management
- Exploiting Architecture

SCR Topics

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Conclusion

- **The critical resource in wireless networking is RF spectrum in space**

- **The Mobile Ad Hoc Networking Protocols, Synchronous Collision Resolution* (SCR) and Node State Routing* (NSR) enable**
  - **The management of RF spectrum in space**
  - **Exploitation of physical layer capabilities**
  - **Resolution of hard wireless networking problems**

- **A different standardization approach is required that**
  - **Retains compatibility with IP networks**
  - **Extends the role of IP networks to manage RF spectrum in space**
  - **Provides a space for innovation that does not require standards**

* Patents pending

MITRE

Impact

- **Our publications have covered many topics in ad hoc networking**

Capacity

J. Stine, G. de Veciana, K. Grace, and R. Durst, "Orchestrating spatial reuse in wireless ad hoc networks using Synchronous Collision Resolution," *J. of Interconnection Networks*, Vol. 3 No. 3 & 4, Sep. and Dec. 2002, pp. 167 – 195.

Quality of Service

J.A. Stine and G. de Veciana, "A paradigm for quality of service in wireless ad hoc networks using synchronous signaling and node states," *IEEE J. Selected Areas of Communications*, Sep 2004.

Channelization and CDMA

J. Stine, "Exploiting processing gain in wireless ad hoc networks using synchronous collision resolution medium access control schemes," *Proc. IEEE WCNC*, Mar 2005.

Directional and Smart Antennas

K. H. Grace, J. A. Stine, R. C. Durst, "An approach for modestly directional communications in mobile ad hoc networks," *Telecommunications Systems Journal*, March/April 2005, pp. 281 – 296.

J. A. Stine, "Exploiting smart antennas in wireless ad hoc and mesh networks," Submitted to *IEEE Wireless Comm Mag.* for Feb 06.

Energy Conservation

J.A. Stine and G. de Veciana, "A comprehensive energy conservation solution for mobile ad hoc networks," *IEEE Int. Communication Conf.*, 2002, pp. 3341 - 3345.

Ad hoc network modeling

J. A. Stine, "Integrating the physical and link layers in modeling the wireless ad hoc networking MAC protocol Synchronous Collision Resolution," *Proc. OPNETWORK*, 2003.

J. A. Stine, "Modeling smart antennas in synchronous ad hoc networks using OPNET's pipeline stages," *Proc. OPNETWORK*, 2005.

Multicasting

J. A. Stine, "Node State Multicasting in wireless ad hoc networks," *Proc. IEEE MILCOM*, Oct. 2005.

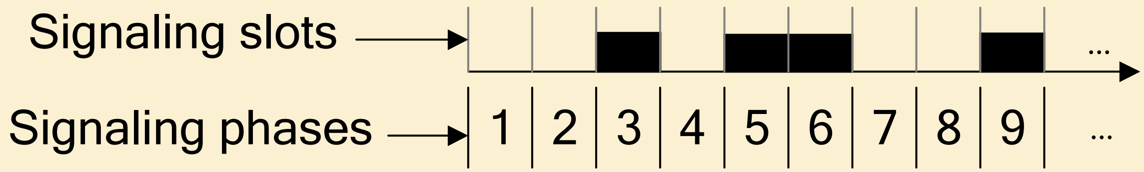
Spectrum Management

J. Stine, "Spectrum management: The killer application of ad hoc and mesh networking," *Proc. IEEE DySPAN*, Nov. 2005.

SCR Topics | NSR Topics

Backup

How well does signaling isolate just one survivor?



- **Consider a signaling design where all phases have one slot**
- **Let p^x be the probability that a contending node will signal in phase *x***
- **A transition matrix may be populated where the element *k*,*s* corresponds to the probability that *s* of *k* contending nodes survive the signaling phase**

$$\mathbf{P}^x_{k,s} = \begin{cases} \binom{k}{s} \left(p^x\right)^s \left(1 - p^x\right)^{k-s} & 0 < s < k \\ \left(p^x\right)^k + \left(1 - p^x\right)^k & 0 < s = k \\ 0 & \text{otherwise} . \end{cases}$$

MITRE

How well does signaling isolate just one survivor? (2)

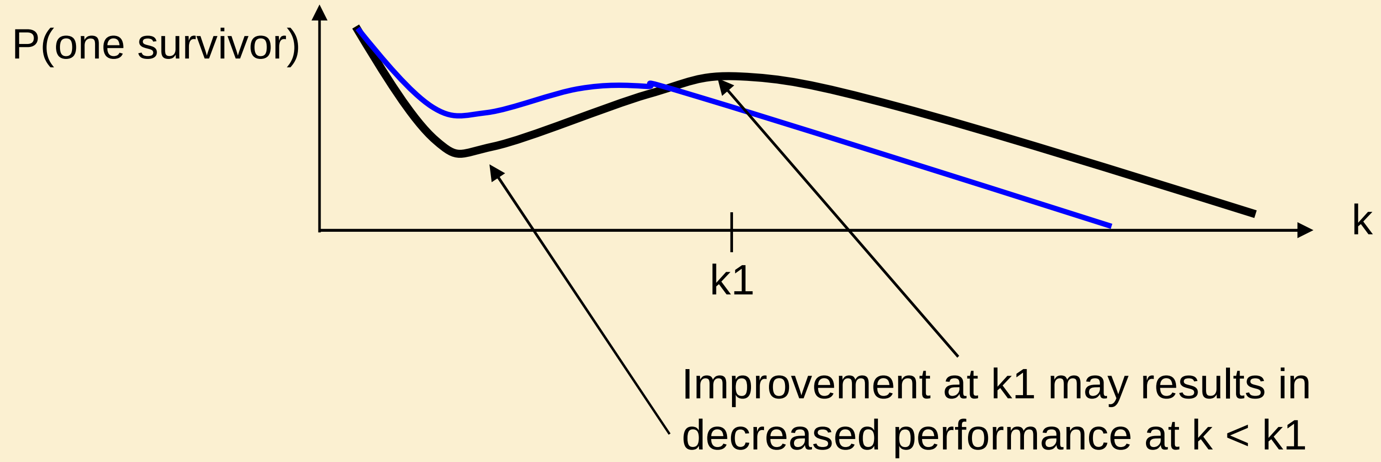
- **The transition matrix of the signaling process with n phases may be calculated**

$$\mathbf{Q}^n = \prod_{x=1}^{n} \mathbf{P}^x$$

- **The probability that just 1 of k contending nodes survives signaling is**

$$\mathbf{Q}^n_{k,1}$$

- **It is easy to optimally select a set of probabilities that maximizes the probability that there will be 1 survivor when there are some k = k1 contenders at the beginning but this problem formulation may result in a lower probability that one survivor remains when there are k < k1 contenders.**



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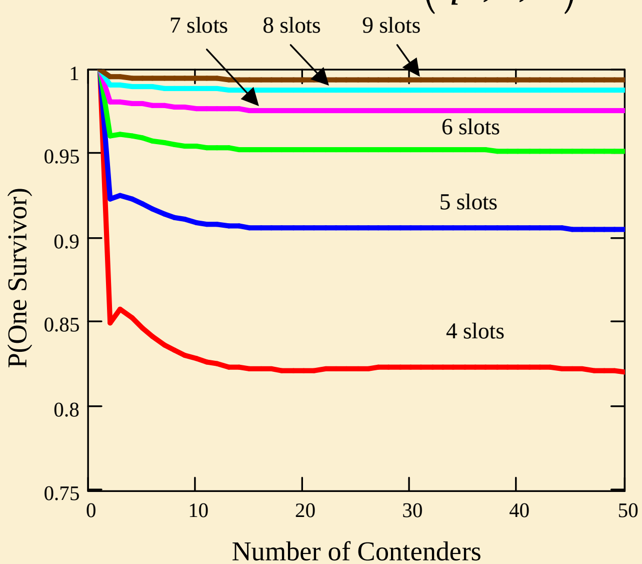
How well does signaling isolate just one survivor? (3)

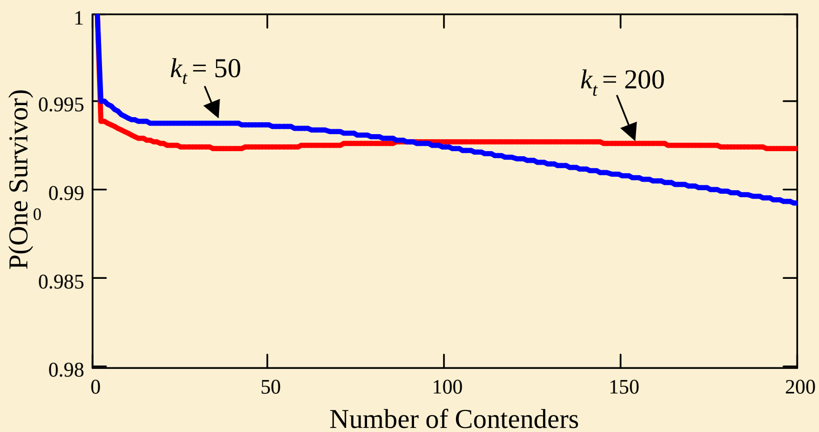
- **A redefined optimization problem**
  - **Let q^n be the set of p^x for an n phase CRS design**
  - **Let k_t be a target density of contending nodes**
  - **Let m be the total number of signaling slots allowed (in this case $n = m$)**
  - **Let $S(q^n,k_t,m)$ be the probability that there will be only one surviving contender**

$$\max_{q^n} \; S\left(q^n, k_t, m\right)$$

$$\text{s.t.} \;\; S\left(q^n, k, m\right) \geq S\left(q^n, k_t, m\right) \qquad \forall k, 0 < k < k_t \; .$$



4, 5, 6 , 7, 8, and 9 single-slot phase designs optimized for a 50 contender density



Comparison of 9 single-slot phase designs optimized for target densities of 50 and 200 contenders

SCR Topics

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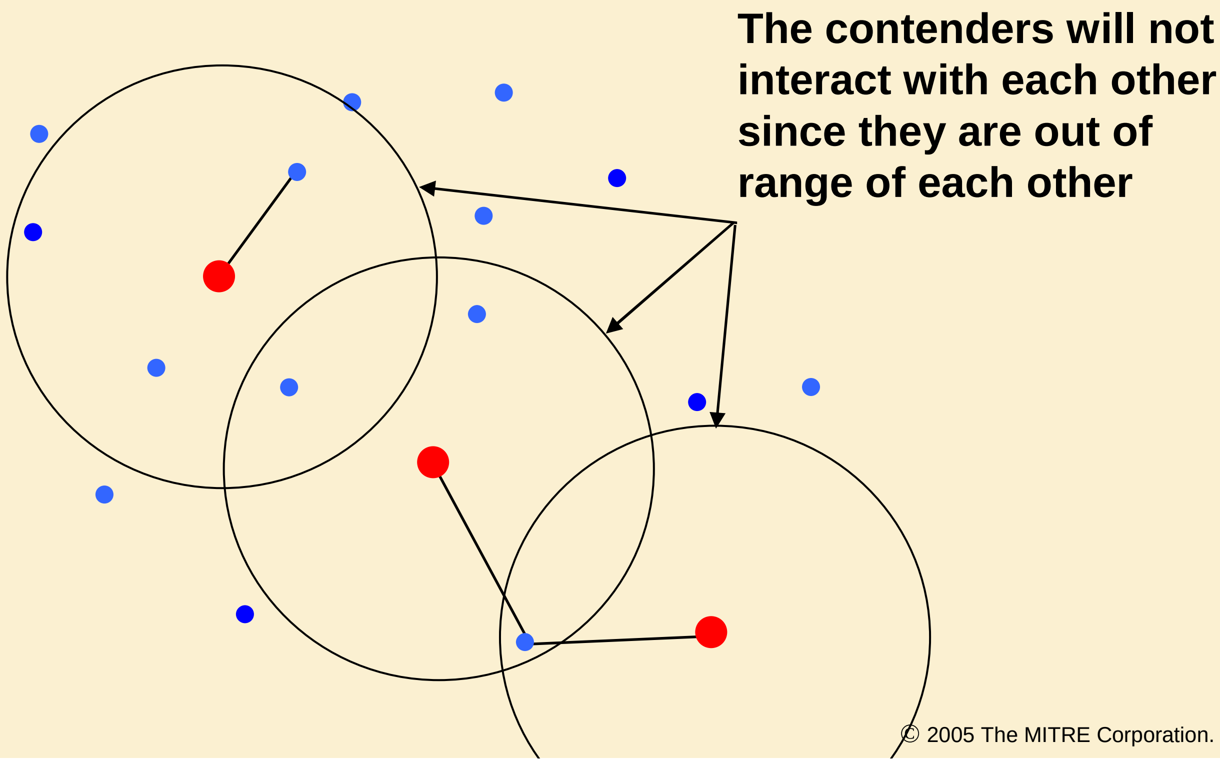
Resolving blocks

- One hop signaling may result in deadlock
  - Two survivors repeatedly win the contention but attempt to send to the same destination thus blocking each other
  - Most likely to occur in lightly loaded and less dense networks
- Signal echoing will break this deadlock



Resolving blocks

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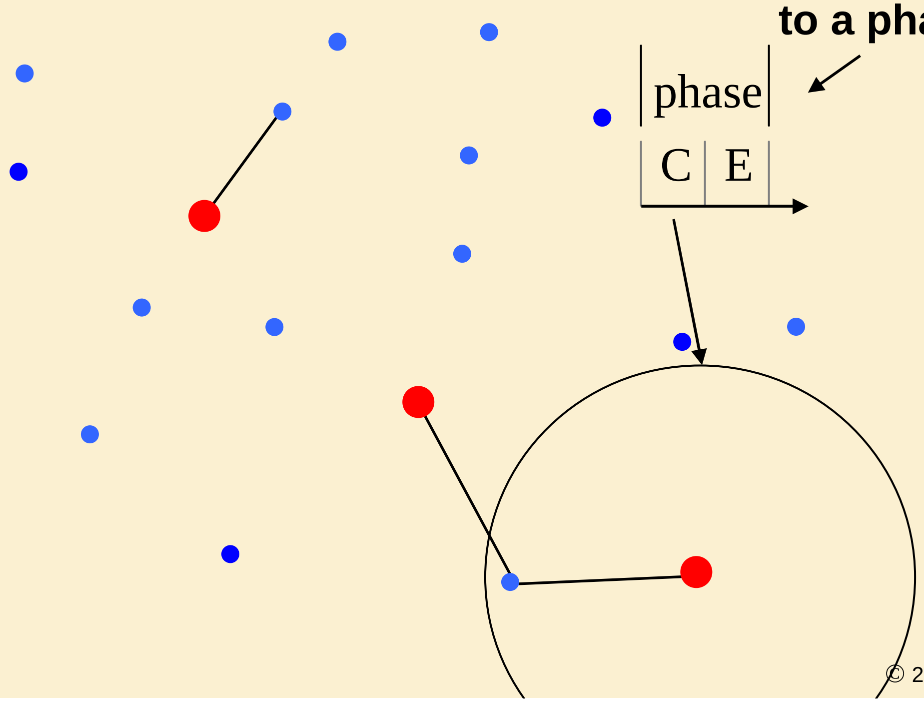
With echoing a contender signals as before but we add a slot to a phase for an echo



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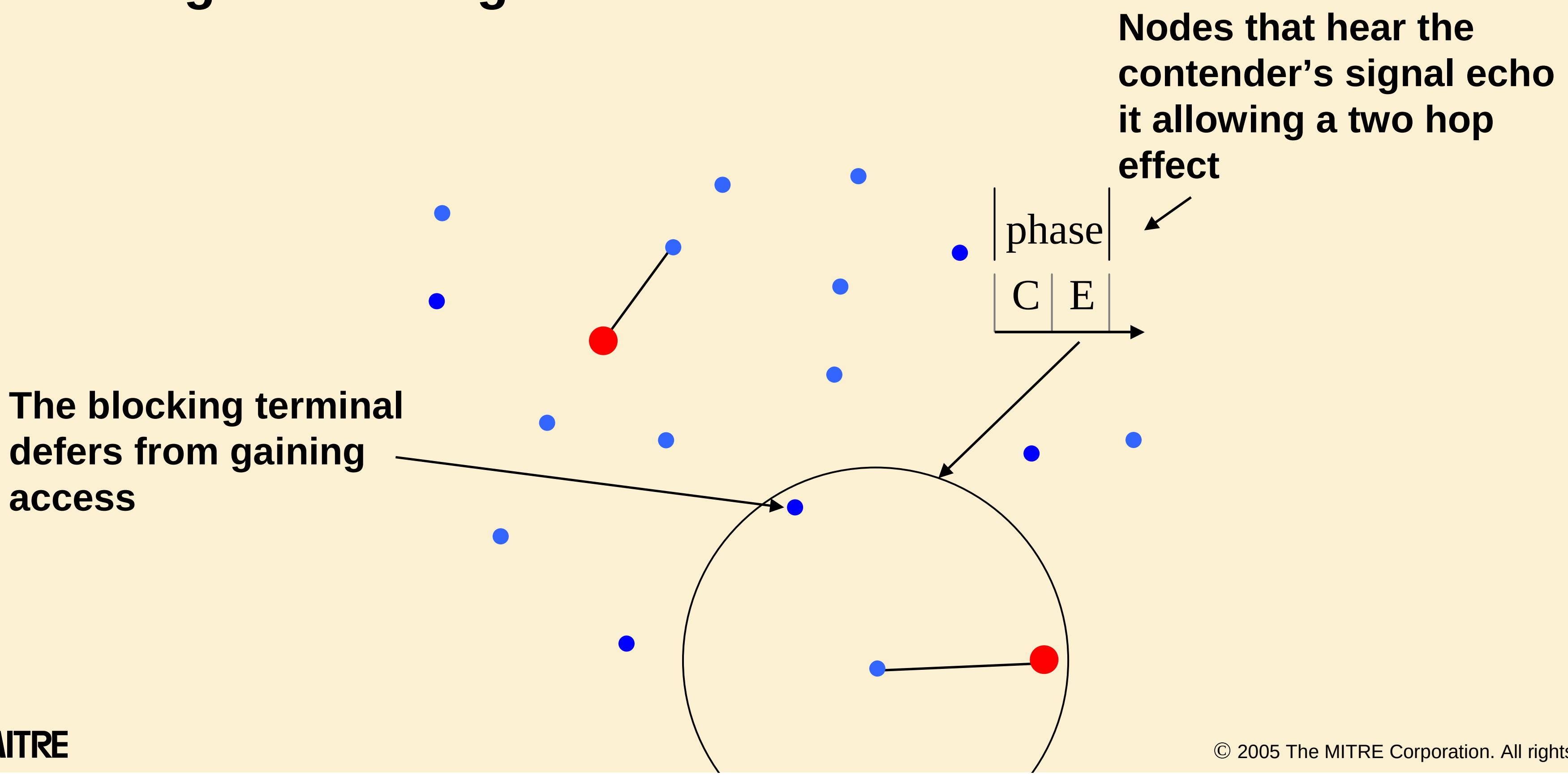

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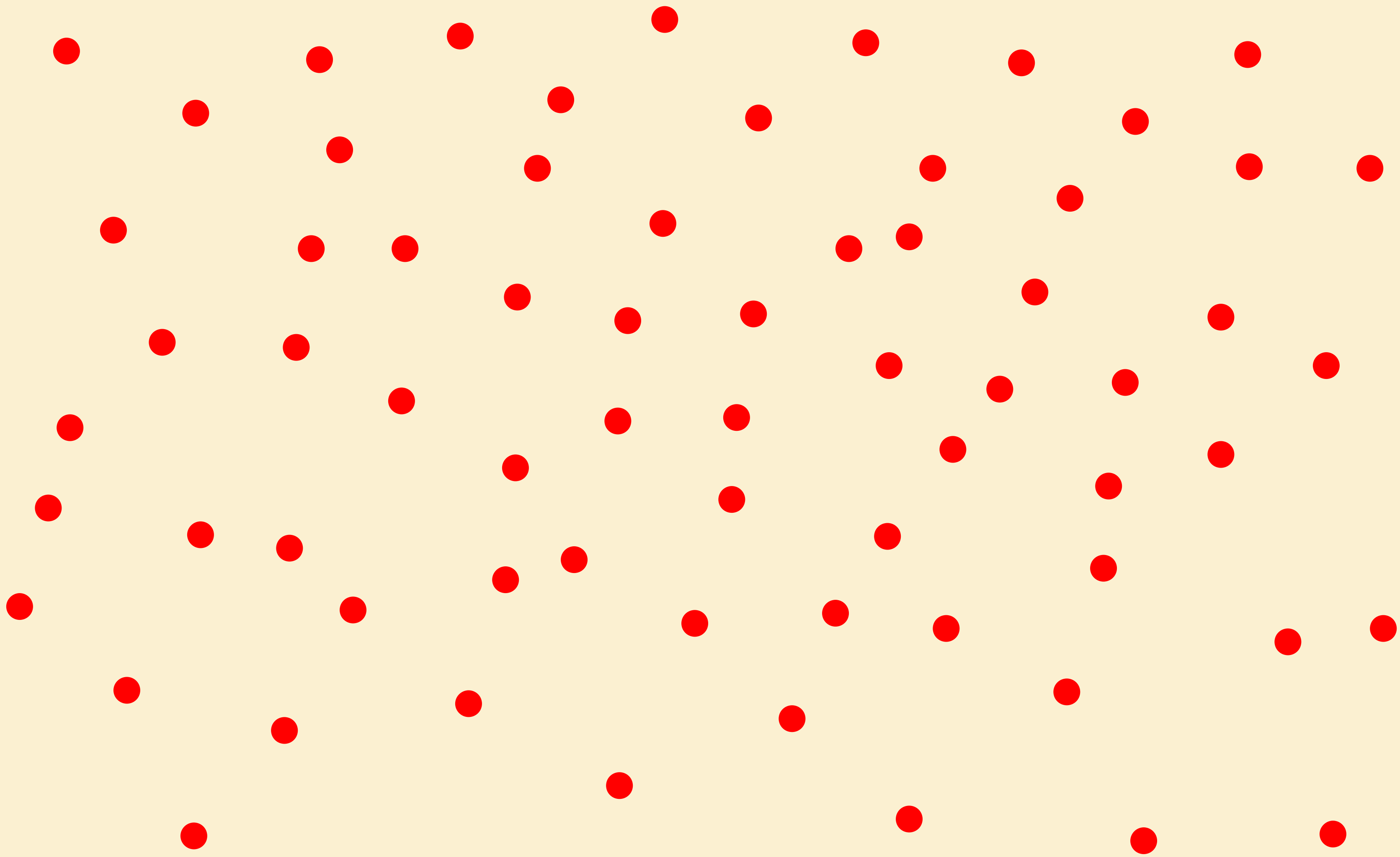
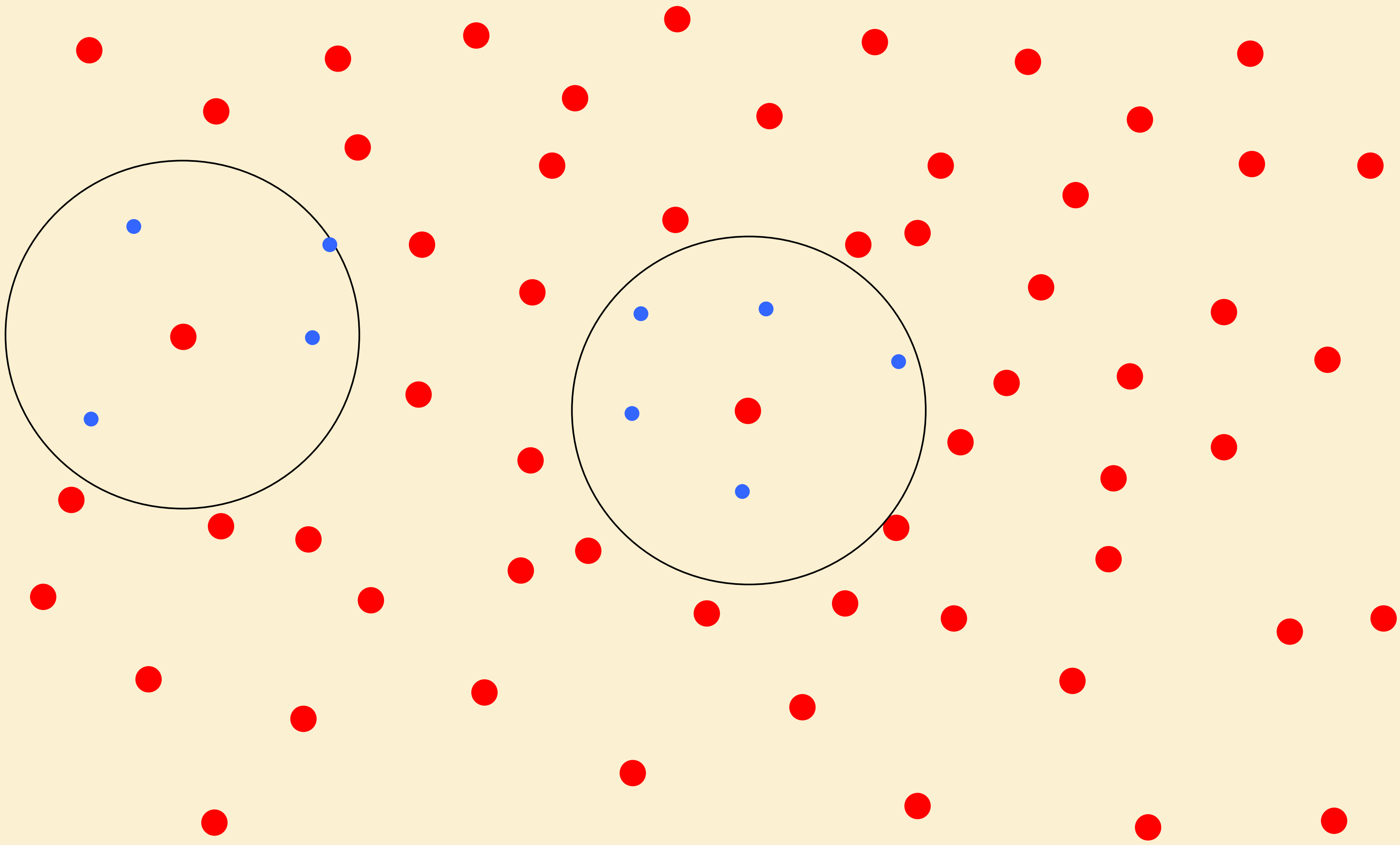
Example of signal echoing (1)



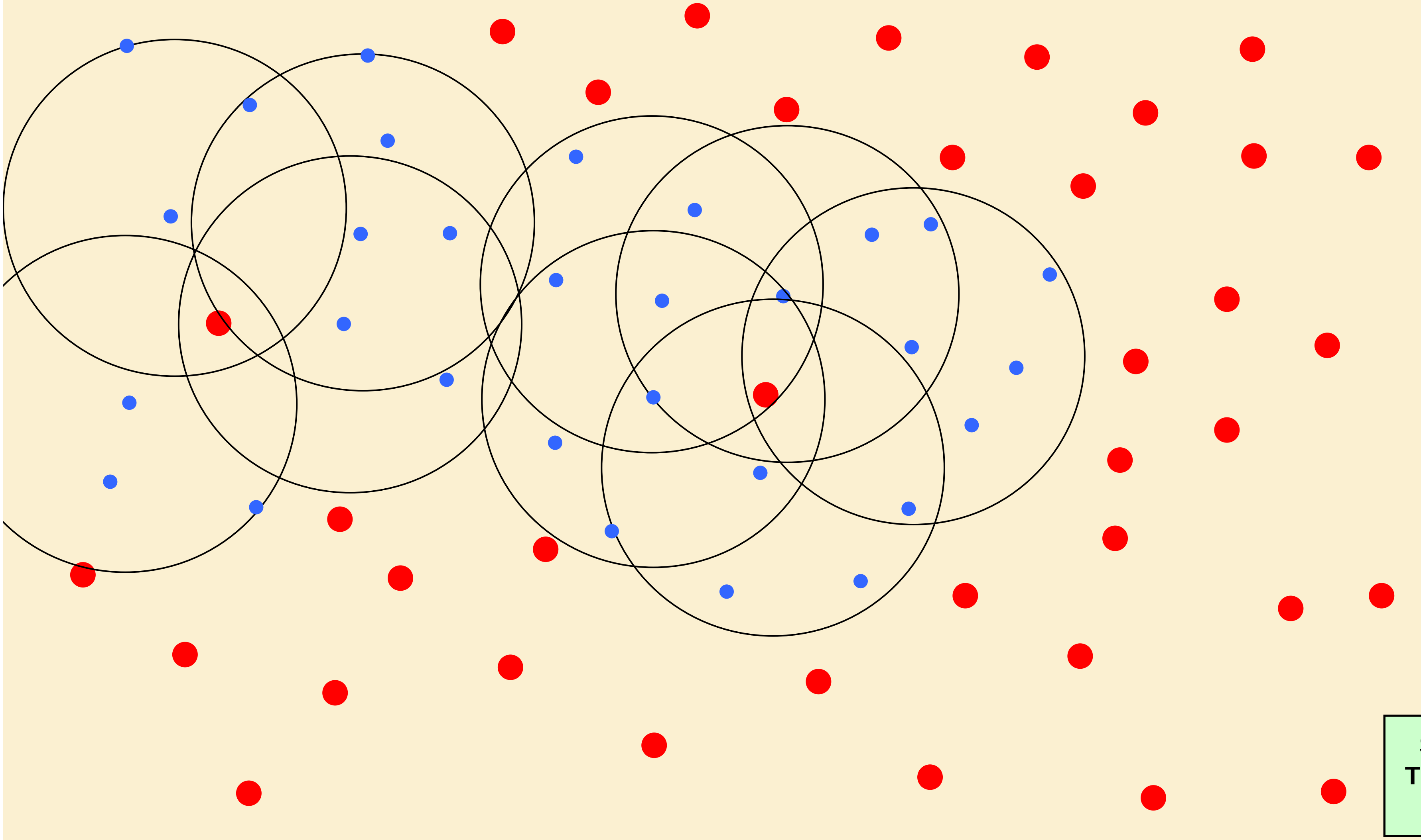
Red nodes are contenders

Example of signal echoing (2)



Signaling has two parts, first a signal by a contender

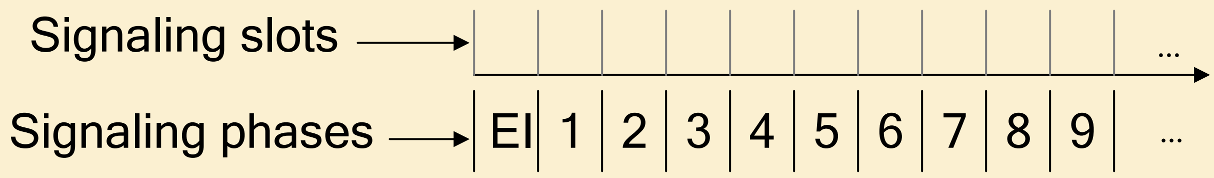
Example of signal echoing (3)



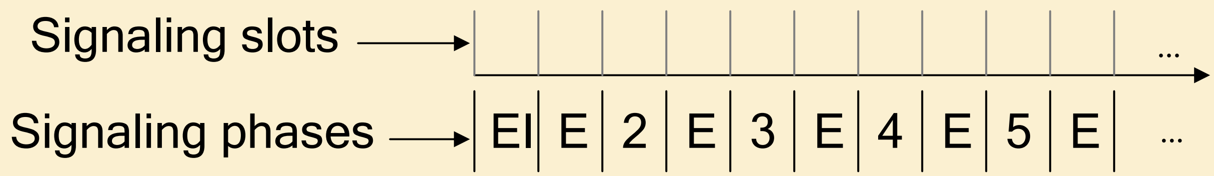
Next, all nodes that heard the contenders' signals echo them

Reactive echoing to breaking blocks

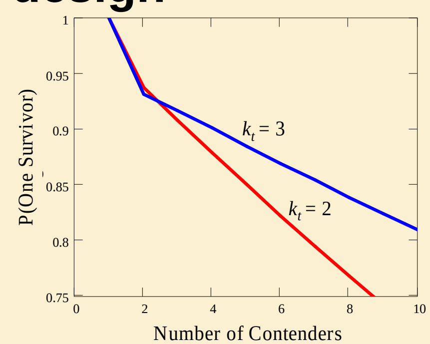
- **Use a hybrid signaling process**
  - **A standard 9 phase design**
  - **A contender can invoke echoing and execute a 5 phase echo design**



  - **A node that signals in the EI slot invokes the echoing design**



  - **All nodes that hear the EI signal echo as appropriate**



- **Trigger to use echoing may be repeated failed exchanges or be the destination of the packet**
  - **Broadcast packets**
  - **Destination is an exposed terminal**

SCR Topics

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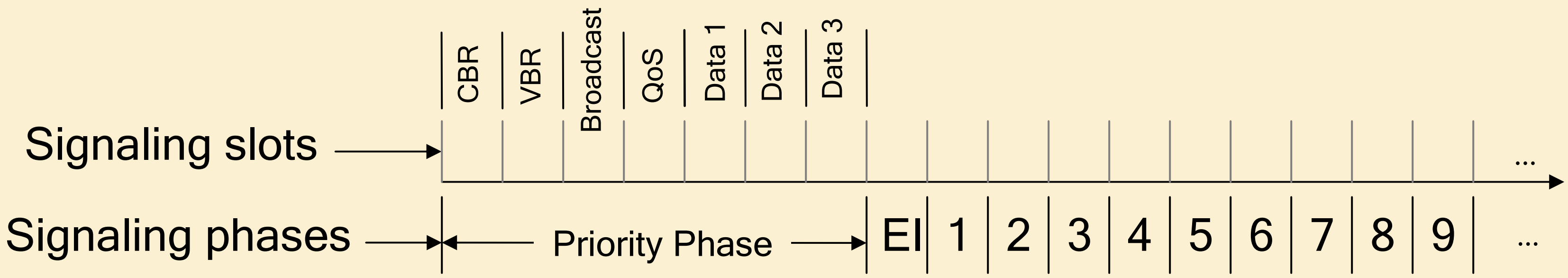
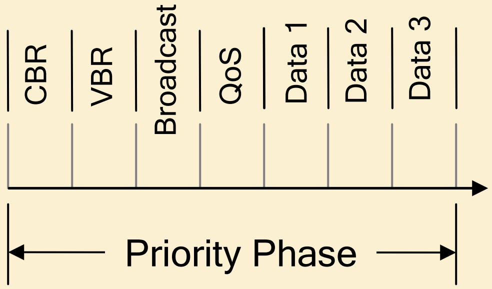
Special features through a priority phase

- We add a multi-slot phase to the front end of the collision resolution signaling that assigns slots to specific services



- This example design illustrates three services
  - Priority access
  - Resource reservation
  - Channel management

Priority access



- In multi-slot first-to-assert phases the node that signals first will win the contention
- Slots may be mapped to differentiate access priority
- Potential characteristics to differentiate priority
  - Packet time-to-live parameter
  - Source significance
  - Operational significance
  - Primary vs secondary spectrum access
- Nodes with the highest priority packets will always gain access first

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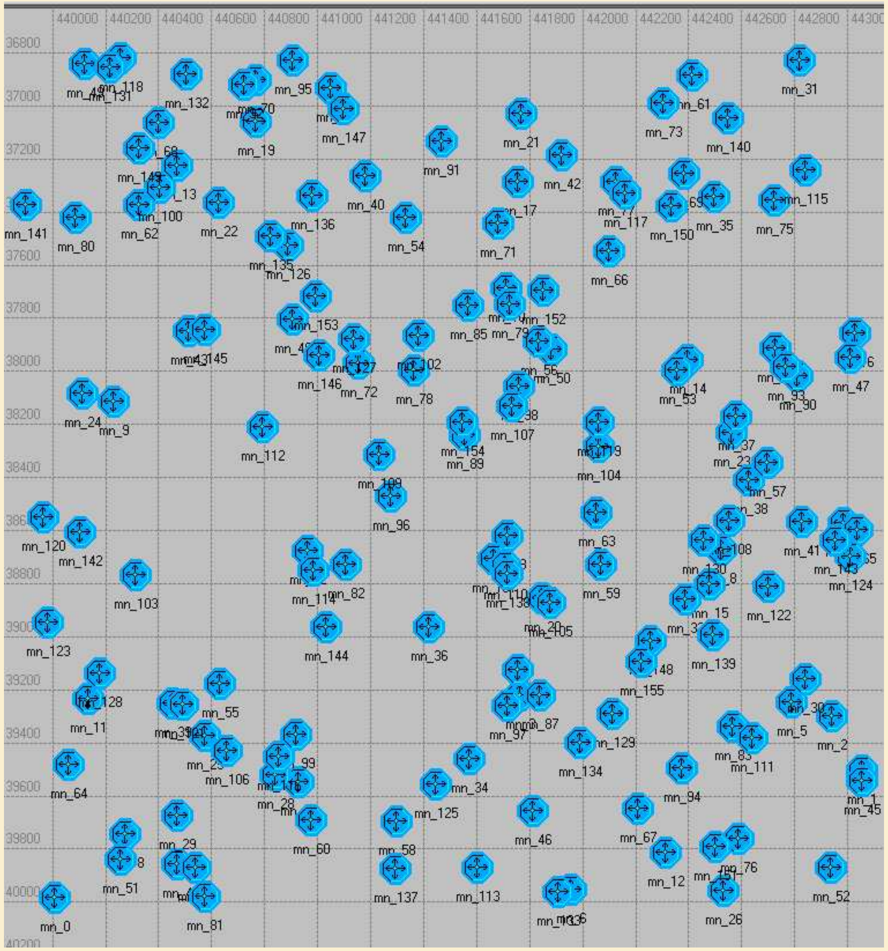
The effectiveness of prioritized access

- **Issue: How well does priority access work.**
- **Experiment:**
  - **156 nodes randomly placed on a toroidally wrapped square surface with a side (7* radio_range) which results in a network with an average degree of 10**
  - **Perfect routing assuming a potential connection when SNR is >10dB**
  - **Poisson arrival of packets uniformly distributed amongst the nodes with randomly and uniformly selected destinations**
  - **Packets are randomly and evenly distributed among four priority levels**
  - **Packets queued by priority earliest expiration time first**



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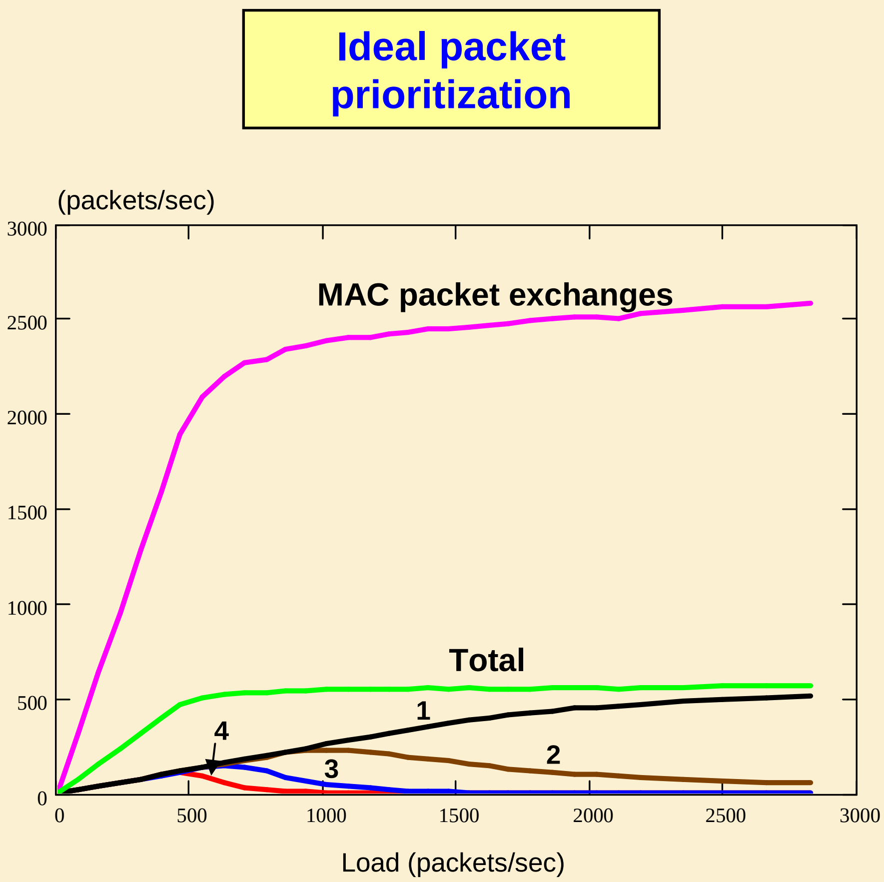
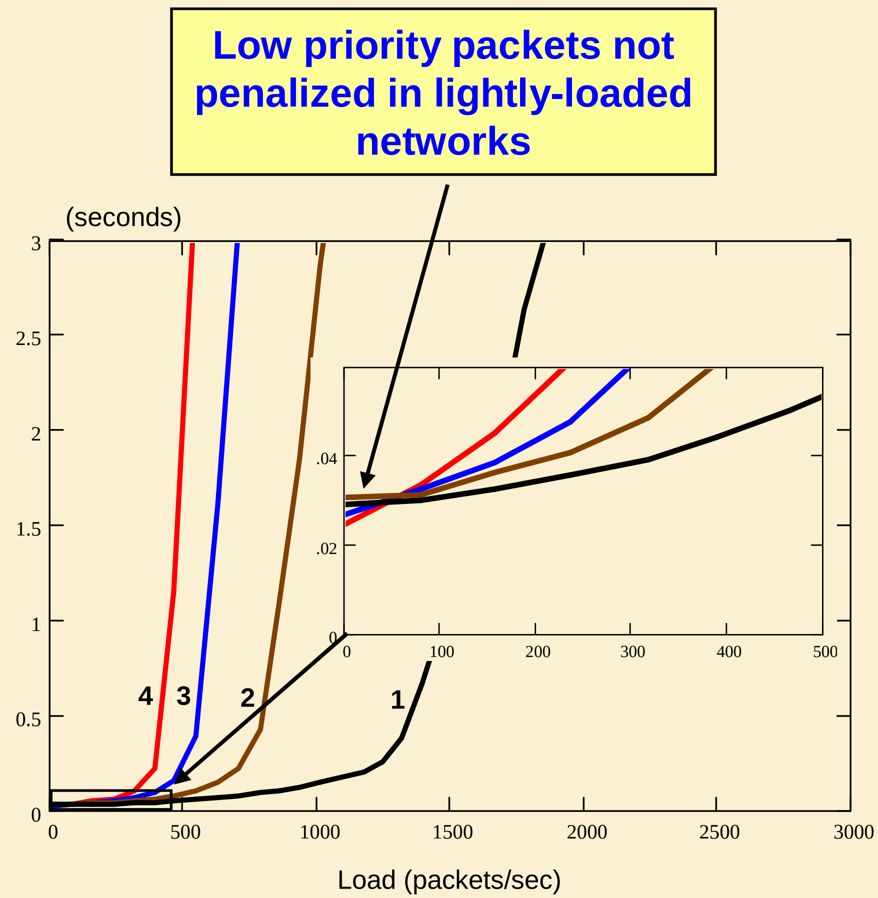
The effectiveness of prioritized access



End-to-end throughput



End-to-end delay

SCR Topics

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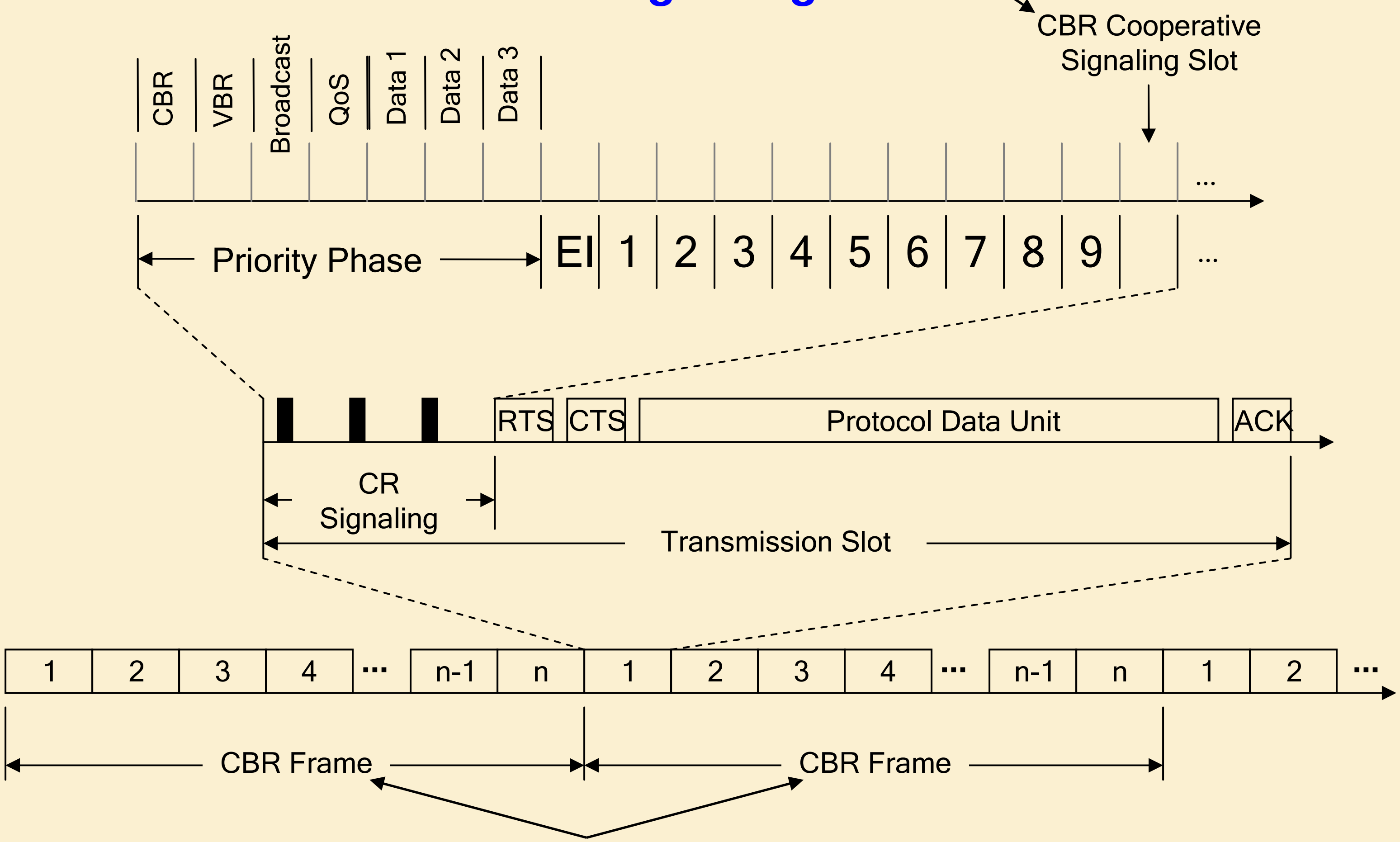
Modified signaling design for priority access, resource reservation, and channelization

Add a cooperative signaling slot



Divide the transmission slots into frames

SCR Topics

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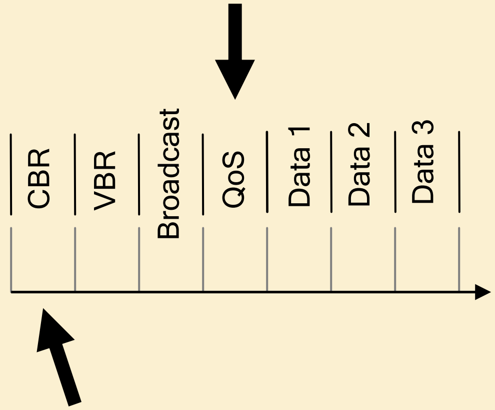
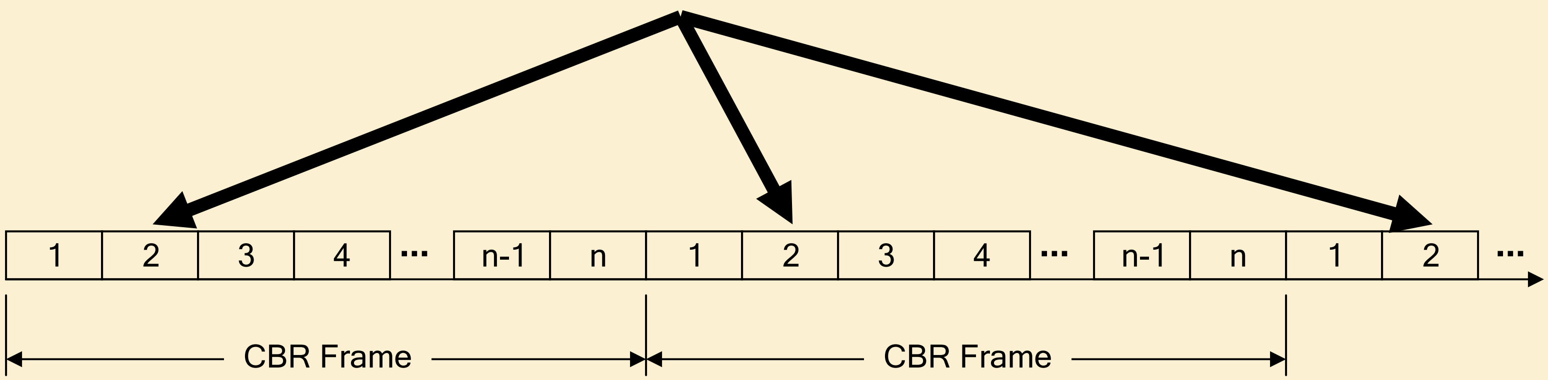
Resource reservation process (1)

- Contenders with a real time stream first contend using the QoS priority

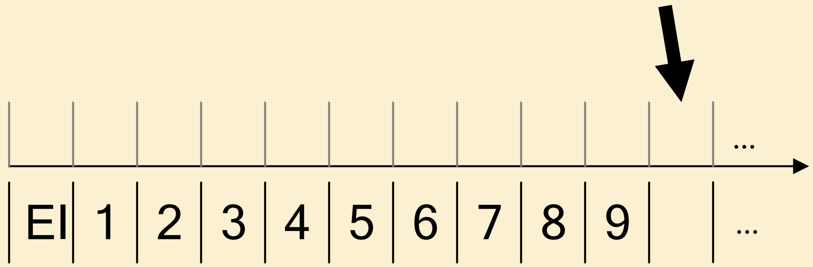


- If packet exchange is successful, that node may use the CBR priority in the same ordinal transmission slot of every subsequent CBR Frame.

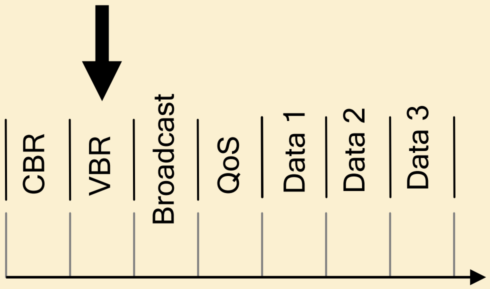


Resource reservation process (2)

- CBR destinations use the CBR cooperative signaling slot (i.e. the first slot of the last signaling phase) to assist in ensuring two-hop exclusive access. Only CBR sources and destinations may use this signaling slot.

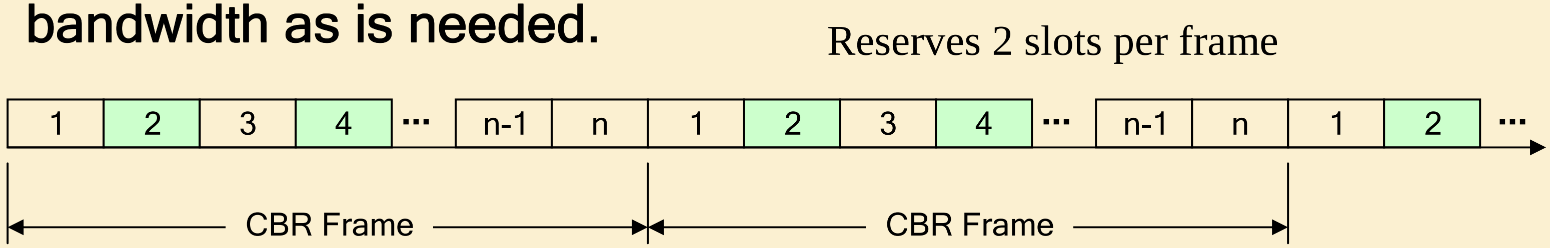


- CBR destinations know who they are since they received traffic in the same ordinal slot of the previous frame that they hear the CBR signaling priority being used
- Sources with a CBR reservation may use the VBR priority in a best-effort sense to send packets from the same stream. This provides efficient support for bursty streams like video.

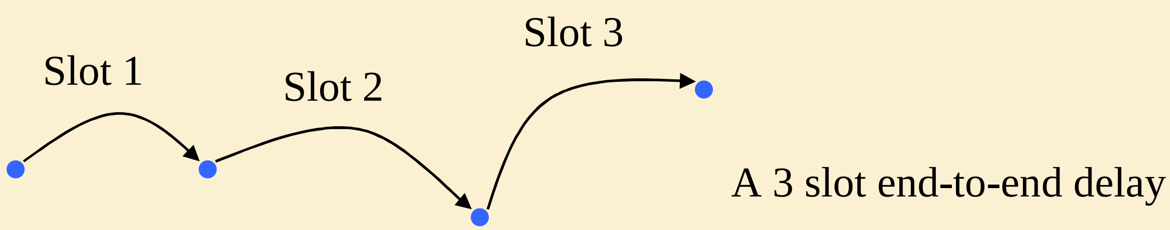


Resource reservation process (3)

- The process may be repeated by a node to reserve as much bandwidth as is needed.



- The process can be repeated by multiple nodes in a series to provide services for multihop streams.
- Multihop reservations can be cascaded to ensure an end-to-end delivery time.



- Nodes hold reservations on a “use-it or lose-it” basis (Unused slots are immediately available).

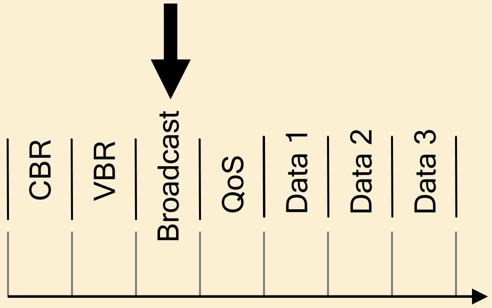
Return to topics

Using multiple channels

- Why use multiple channels
  - It increases the capacity of the network
  - LPI/LPD waveforms already consume wide bands of spectrum that can be channelized (e.g. DSSS)
- Why is it challenging
  - All nodes have a need to listen on a common channel to receive broadcasts that support topology discovery
  - In most contention protocols, it is ambiguous on which channel to listen
  - Near-far effect is an issue when DSSS CDMA is used to create channels
- How is the problem normally solved
  - Touch and go (T&G)
  - Hop and stay (H&S)
  - Scheduling in TDMA type protocols (Not a contention protocol)
- What goes wrong in T&G and H&S protocols
  - Ambiguity as to which nodes are busy
  - Exacerbates hidden node effects (Near-far problem with DSSS)

Channelizing using SCR

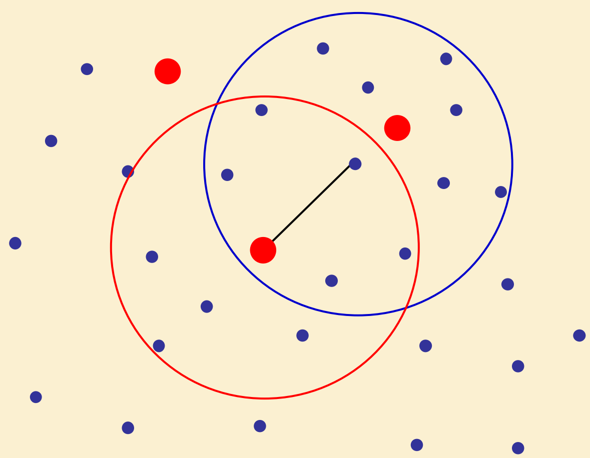
- How are channels assigned in SCR
  - A shared broadcast channel
  - Receiver directed peer-to-peer channels (Nodes select their channel and advertise it to their neighbors)
- How do destinations know which channel to listen to
  - Use priorities to distinguish broadcast and peer-to-peer transmissions



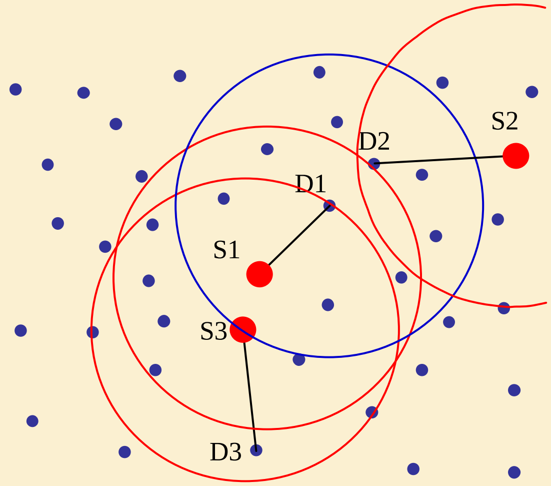
  - Neighbors that hear the broadcast priority used to gain access listen on the broadcast channel otherwise they listen on their peer-to-peer channel
- CRS and synchronization creates a node geometry that mitigates the near far effect

SCR Topics

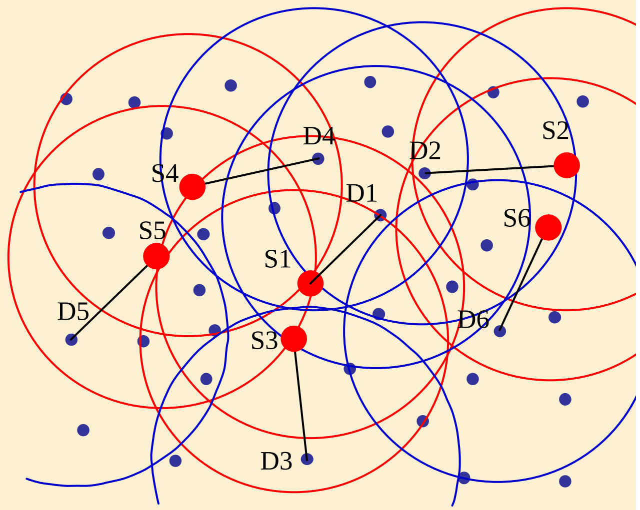
The advantage of synchronous protocols-1



Why PG cannot be exploited with the 802.11 MAC



Both sources and destinations must be separated from each other



Sources and destinations may be clustered together

Asynchronous Access

Synchronous Access

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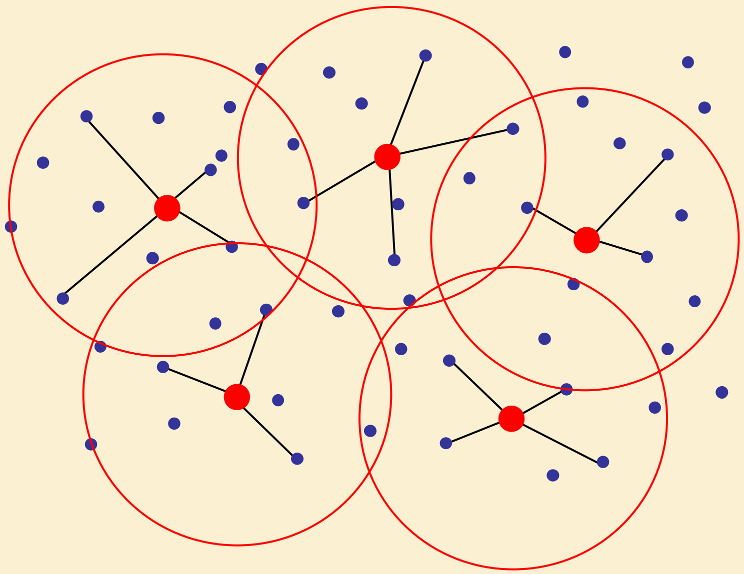
The advantage of synchronous protocols-2



If sources are separated from each other we can support one to many communications

Synchronous Access

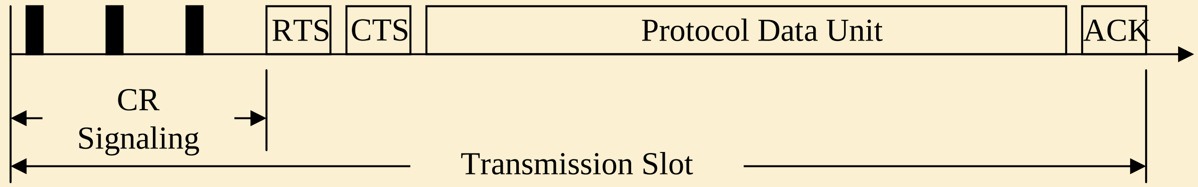
SCR Topics

Energy conservation

- Energy can be conserved by using low energy states
- Using low energy states has great potential
  - At any one time more nodes can be conserving energy using a low energy state than can conserve energy using a low transmit power
  - Only the use of low energy states can exploit low duty cycles to conserve energy
- Entering a low energy state usually means removing a node from the network while it is in the low energy state
- Sources need to be aware of when nodes are in low energy states
  - Should hold traffic when in a low energy state
  - Should forward traffic when destinations are awake
- Best protocols
  - Make dozing schedules implicit
  - Minimize the time nodes must remain awake before learning that they can enter a low energy state

Default energy conservation mode in SCR

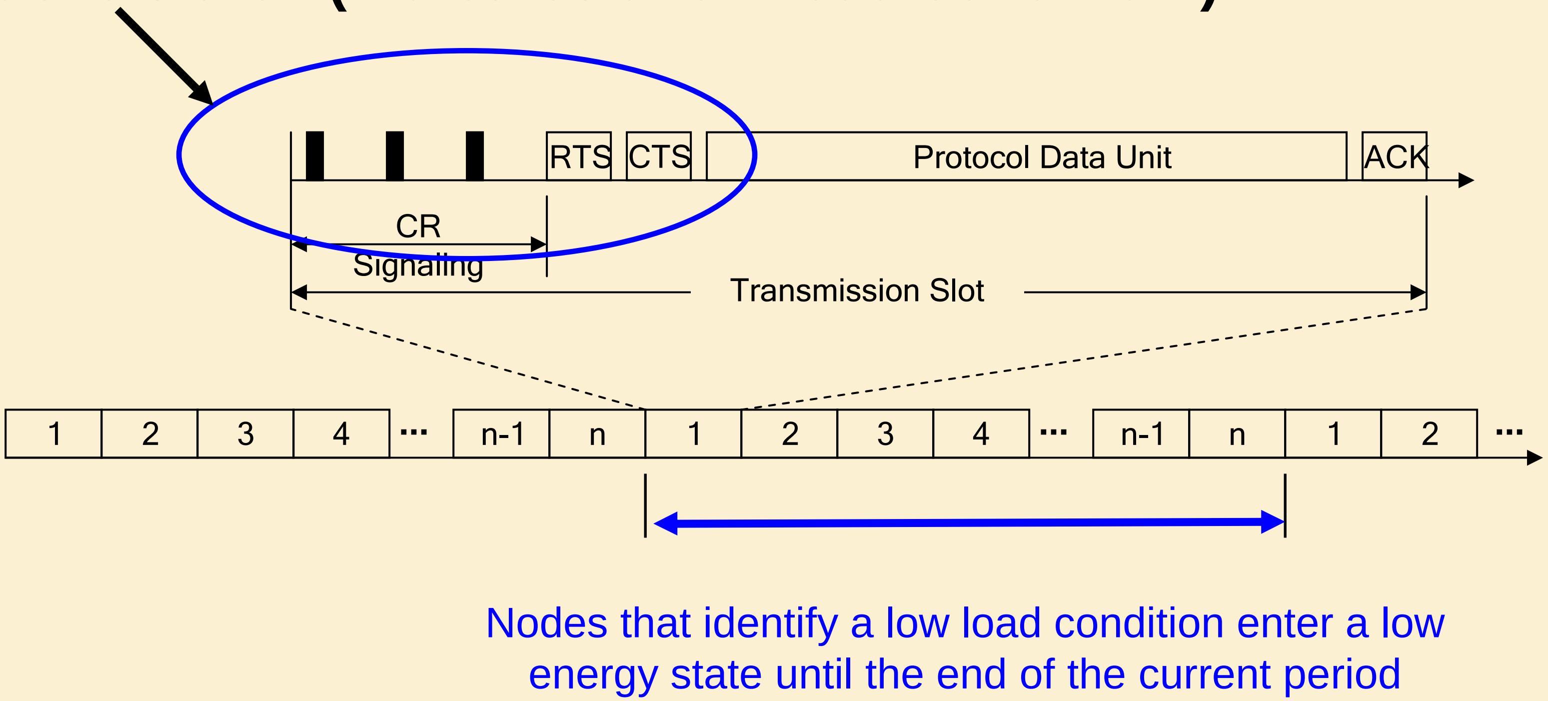
- Nodes enter a low energy state in every slot that they do not participate in a packet exchange



- Prior to the PDU transmission, every node in the network knows if it will participate in an exchange
- Nodes not exchanging packets in the transmission slot enter a low energy state until the beginning of the next slot

Periodic dozing method

- A single dozing period (i.e. x transmission slots starting at time t) is established for the network
- A node that senses no nodes contending may enter the doze state. (Indicates a low load condition.)



- Nodes wake-up at the end of the period and stay awake until they next sense an idle transmission slot.

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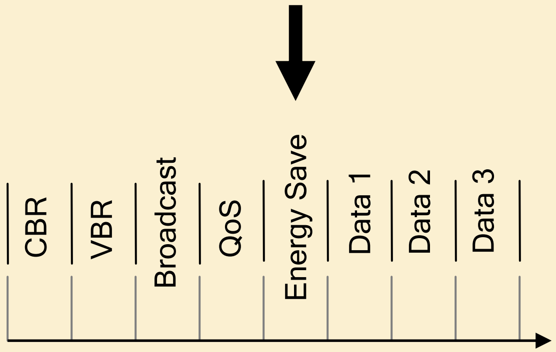
Coordinated dozing method

- Energy constrained nodes establish their dozing period and announce it to their neighbors.
- Neighbors hold traffic for the dozing node but can use a special “energy save” priority to access the channel.
- Dozing nodes wake-up and stay awake so long as contenders contend using the “energy save” or higher access priority signaling slot.



- This technique allows battery powered nodes to exploit nodes with generative power sources to conserve energy

SCR Topics

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Notes on adaptive antennas

- **Adaptation can either point a mainbeam or it can steer nulls (i.e. optimize SIR) but it cannot do both**
  - **Beam adaptation uses direction of arrival algorithms to determine direction to a transmitter and then uses phase methods to steer the beam (requires a calibrated array)**
  - **Null steering use various techniques to optimize signal-to-interference and noise ratio by adapting phases and weights to control directional gain**

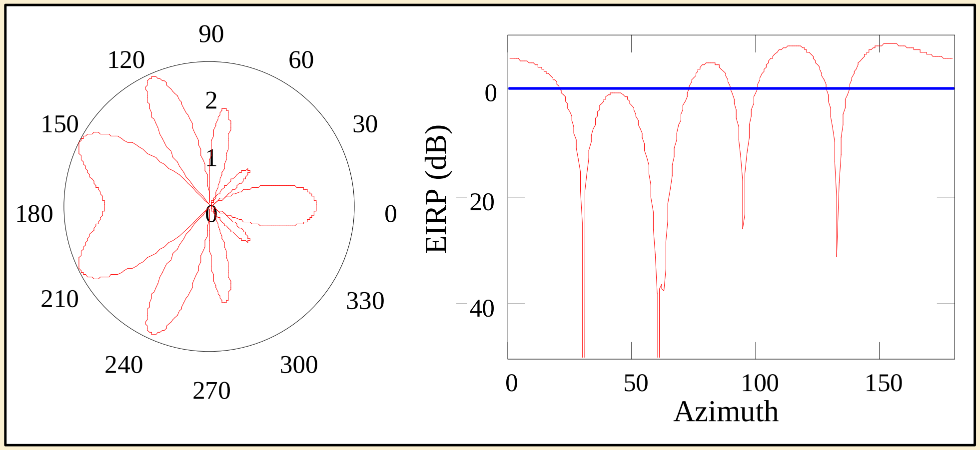
(n, d, θ, γ_1, γ_2,…)

n – number of elements

d – spacing between elements

θ – pointing direction

γ – null directions



Observations:

1) Narrow nulls,
2) Pointing direction on the side of a sidelobe
3) High gain in extraneous directions

Example adaptation for (8, .5, 100, 30, 60) normalized to 0 dB at 100° using the Maximum SINR technique

Conditions for smart antenna use

- **Simple pointing**
  1. **Know where to point**
  2. **Know where not to point**

Protocols direct the physical layer

- **Adaptive pointing and null steering (*also necessary for MIMO*)**
  3. **Capture the condition**
  4. **Prevent multiple transmitters in the near same direction**
  5. **Prevent congestion**
  6. **Preserve the condition**

Protocols create the conditions that allow the physical layer to adapt effectively

SCR creates the conditions for adaptive antenna use

- Adaptive pointing and null steering conditions
  3. Capture the condition
  4. Prevent multiple transmitters in the near same direction
  5. Prevent congestion
  6. Preserve the condition

- SCR creates all the conditions for adaptive pointing and null steering
  - The RTS-CTS exchange allows both sources and destinations to identify where interference is coming from
  - CRS prevents multiple contenders in the same direction
  - CRS prevents congestion
  - Conditions are preserved throughout the PDU and ACK transmissions

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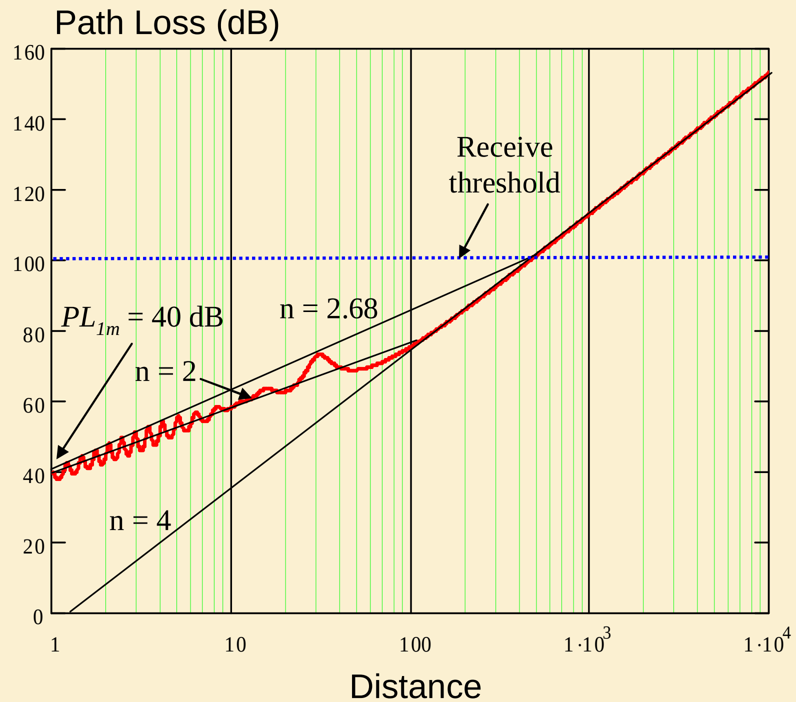
Pathloss

- Observations
  - Pathloss may vary dramatically over short distances due to multipath effects
  - Radios can receive and detect signals with strengths that vary over a wide dynamic range, over 10^6 times
- Conclusion
  - It is not practical to predict pathloss with precision
  - Precise prediction is not necessary to infer connectivity

Path loss models

- Path loss generally increases as a power law function of distance
  - $PL = PL_{1m}\, d^n$ ⟶ $\log(PL) = \log(PL_{1m}) + n \cdot \log(d)$ ⟵ A linear model
    - PL_{1m} is the path loss after the first meter of propagation
    - d is the distance of propagation in meters
    - n is the path loss exponent



Linear approximation of the 2-ray propagation model

Propagation maps

- **Pathloss can be modeled with two values, the 1-meter intercept and a pathloss exponent**
- **Pathloss is not the same to all destinations so we can use directional diversity to differentiate different pathloss characteristics**
- **A propagation map is an efficient way to specify different exponents for different directions**
  - **A variable size data structure that uses 8 bit words**
  - **Can specify 256 different exponent values, 256 different longitudes (θ), and 180 (by choice) different latitudes (ϕ)**
    (Larger words can support more values**)**
  - **Can specify different path loss exponents for 46,080 directions but the goal is to use the smallest data structure possible and so the propagation map has a dynamic size**
  - **The propagation map has the form**
    (0, 0, *n00*, *θ01*, *n01*, … *θ0x*, *n0x*, 255, *ϕ1*, *θ10*, *n10*, *θ11*, *n11*, …, 255, 180)
  - **ϕ = 0, θ = 0, θ = 255 and ϕ = 180 occur predictably so we can drop most from the structure**
  - **Use θ = 0 and 255 as delimiters in an abbreviated data structure**

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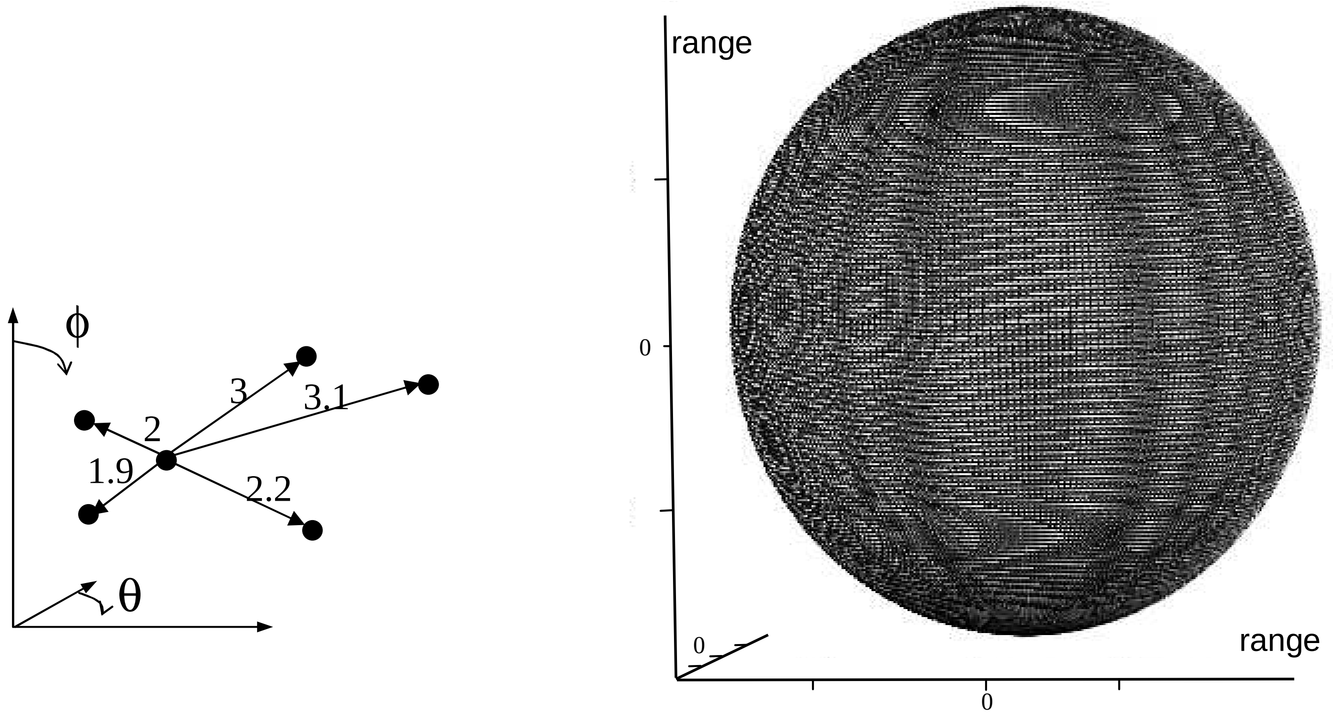
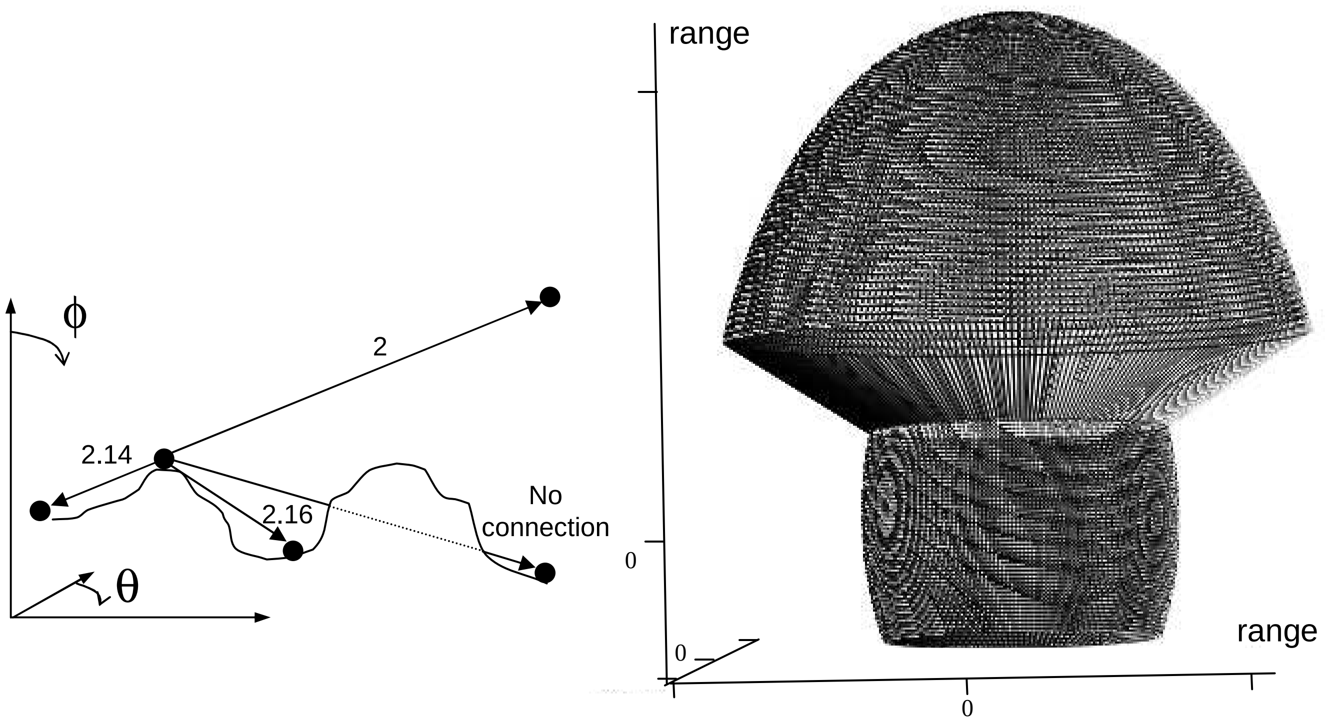
Example propagation map (1)



Propagation map → (3.1, 0)

Since the larger exponent would predict connectivity for all the destinations, the propagation map consists of a single exponent

Example propagation map (2)



Propagation map ⟶ (2, 255, 70, 2.16, 255, 120, 7, 0)

Short data structure that predicts connectivity to all observed nodes but not to a known node that cannot be reached

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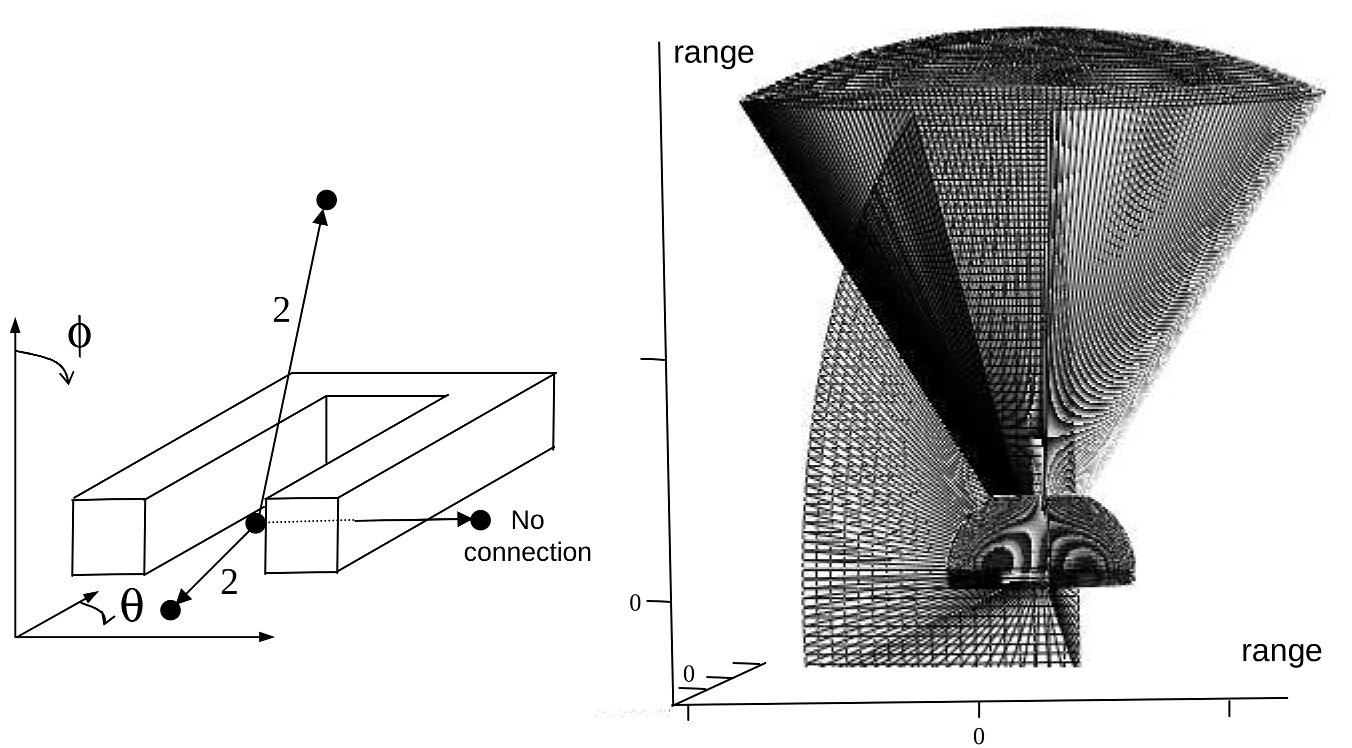
Example propagation map (3)



Propagation map → (2, 255, 30, 2.5, 120, 2, 140, 2.5, 255, 100, 7, 0)

Data structure that captures propagation in an urban draw

NSR Topics

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Advantages of Node State Routing

- The number of node states is independent of network degree
  - A network of *n* nodes with degree *d* has *n* x *d* link states
  - One node state per node regardless of degree
- Node states provide more information
  - In link driven protocols link metrics are determined by end nodes
  - In NSR, metrics can consider states of end nodes and their neighbors
- Routing metric selection is independent of the link discovery process
  - In link driven protocols
    - Link metrics are derived at the time of discovery
    - Having more than one metric requires more pairwise coordination
    - May require a separate protocol implementation for each metric
  - In node state routing
    - Link metrics are derived at the time of routing table calculation
    - Metrics require pairwise use of nodes states but no coordination between nodes

Advantages of Node State Routing (2)

- NSR can be both predictive and adaptive
  - Link driven protocols can predict the loss of a link but requires a discovery process for new connections
  - Node state information can support predicting future connectivity
- Node state quality can be leveraged to reduce overhead
  - A node advertises its link states at a rate governed by the most volatile link
  - A node advertises its node state at a rate dependent on the rate at which it changes
- Node states can support most QoS heuristics
  - In networks using link driven routing protocols, each protocol normally requires its own state discovery and state dissemination mechanism
  - Node state dissemination can be used to disseminate all network state information

NSR Topics

MANET routing protocol scaling

- Routing protocol scaling is a major issue in MANET
  - Overhead in proactive protocols increases at the rate of n^2, *n* different sets of information repeated by the *n* nodes
  - Overhead in reactive protocols increases with the quantity of traffic and with the number of nodes
- MANET routing protocol performance is extremely sensitive to the scenario
  - Scenario components: number of nodes, node movement, environment, and traffic
  - A case can be made to prefer most any protocol over another by selecting the scenario
  - Protocols can be tuned to support a scenario by changing the configurable parameters which also affect scaling
    - Rate of link state updates
    - Lifetime of a route

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Node State Dissemination

- In NSR, node states are diffused through the network at a rate that decreases with distance as part of a scheme to achieve scaling by exploiting fisheye scope and distance effect
  - Fisheye scope
    - Nodes have a relatively current view of neighboring nodes' states and a hazy view of distant nodes' states
    - As packets move toward destinations they arrive at nodes with increasingly better views of the topology near the destination
  - Distance effect
    - The further nodes are separated from each other the less effect their relative movement has on the direction between them so next hops are usually unchanged
    - Routing algorithms tolerate the stale information and predict the same next hops
- Node *i* passes-on node *j*'s states at a rate that is a function of the distance, d_{ij}, between the nodes

$$\Delta T\left(d_{ij}\right) = \begin{cases} \Delta T_1 & d_{ij} \leq 1 \\ c \cdot d_{ij} \cdot \Delta T_1 & d_{ij} > 1 \end{cases}$$

- ΔT_1 is a base retransmission rate and c is some constant

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NSR Scaling

- NSR is a hybrid protocol that uses a proactive mechanism that is forced to scale and uses a reactive mechanism to recover from routing errors
  - Scaling is forced by limiting the rate at which each node can disseminate node states (e.g. one node state update packet per 100 transmission slots)
    - Each node state update packet will include the source's node states and a few others depending on the size of a transmission slot and the number of node states that are tracked
    - A heuristic is employed to select which overdue node states should be advertised in the next node state packet
  - Recovery is triggered by the observation of routing loops
    - Loops occur because nodes have different views of the network
    - Recovery entails broadcasting a relevant subset of the nodes states before forwarding the packet again
    - In this manner all nodes in the loop synchronize their view of the network

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Quality of service in ad hoc networks

- Quality of service protocols consist of three components
  - Measures of network state and ways to observe them
  - Mechanisms to collect and disseminate the state information
  - Heuristics that use the state information
- Often these protocols exist in addition to routing protocols
- NSR provides a unified mechanism for the collection and dissemination of network state information thus reducing the overhead burden associated with implementing QoS protocols
- NSR can also exploit SCR’s reservation mechanism to support streamed traffic

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Quality of Service Routing

Metric	Objective	Description	Relevant States
Energy Conserving	Conserve energy at energy constrained nodes to prolong battery life	The routing metric of a connection is made proportional to the amount of energy required to use the end nodes. This includes the amount of energy used by the source to transmit the packet and the amount of energy used by the connection destination to receive and process the packet. These costs are reduced for nodes that are not energy constrained and may be increased for nodes nearing the end of their battery life. Routing may also try to bypass nodes that are implementing a dozing schedule by penalize connections using these nodes. See [40] for more details.	1-meter path loss, propagation map, cost, dozing offset, dozing period, dozing state, energy state, receive fraction, location
Reliability	Use connections that are least likely to suffer interference	The routing metric is made proportional to path loss. This metric complements the SCR MAC. Since the SCR MAC separates contenders prior to packet transmission based on radio signal range, connections to destinations with low path loss are more likely to succeed on account of signal capture and the decreased probability that another contention survivor will also select it as a destination.	1-meter path loss, propagation map, location
Congestion Avoidance	Use connections through regions of the network that are least used	The routing metric is made proportional to the traffic queued at the source and destination ends of a connection and at their neighbors.	location, queue size
Stream Support	Use connections that are likely to persist for a long time and where transmission slots can be reserved.	The routing metric is made proportional to the expected longevity of the connections based on the understanding of movement of nodes. Preference would be given to connections between stationary nodes	1-meter path loss, propagation map, location, CBR bitmap, time stamp, velocity, direction
Trust	Use connections between nodes that are trusted	The routing metric is made proportional to the trustworthiness of the end nodes. Trustworthiness may be assigned manually to nodes, be assigned through an authentication mechanism, or be created by the context of the node's activities such as where they are and where they have been over time.	address, IP addresses, 1-meter path loss, propagation map, location, time stamp, velocity, direction
Long Distance Delivery	Use present and anticipated connections based on the expected progress of packets through a network	Connections are inferred based on anticipated location. The metric is then made proportional to the expected reliability of that prediction. Routing tables formed from this metric would be used for low priority packets that are expected to take a long time to move through the network to their final destination.	1-meter path loss, propagation map, location, time stamp, velocity, direction

NSR Topics

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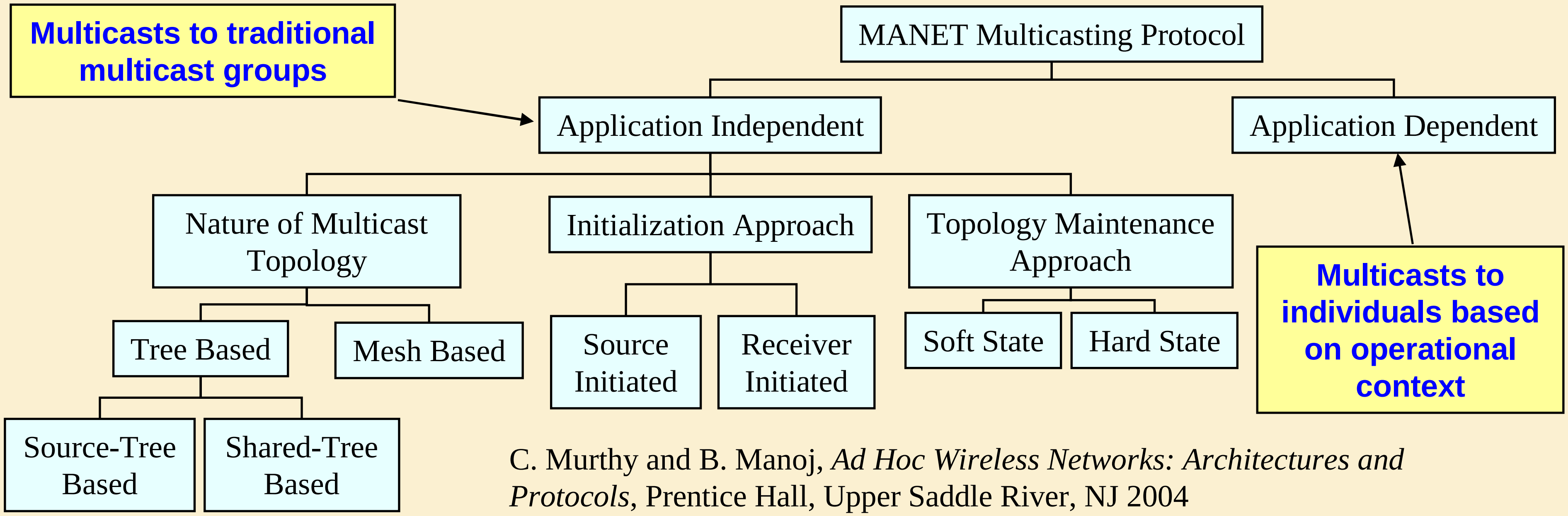
Wireless multicasting protocols

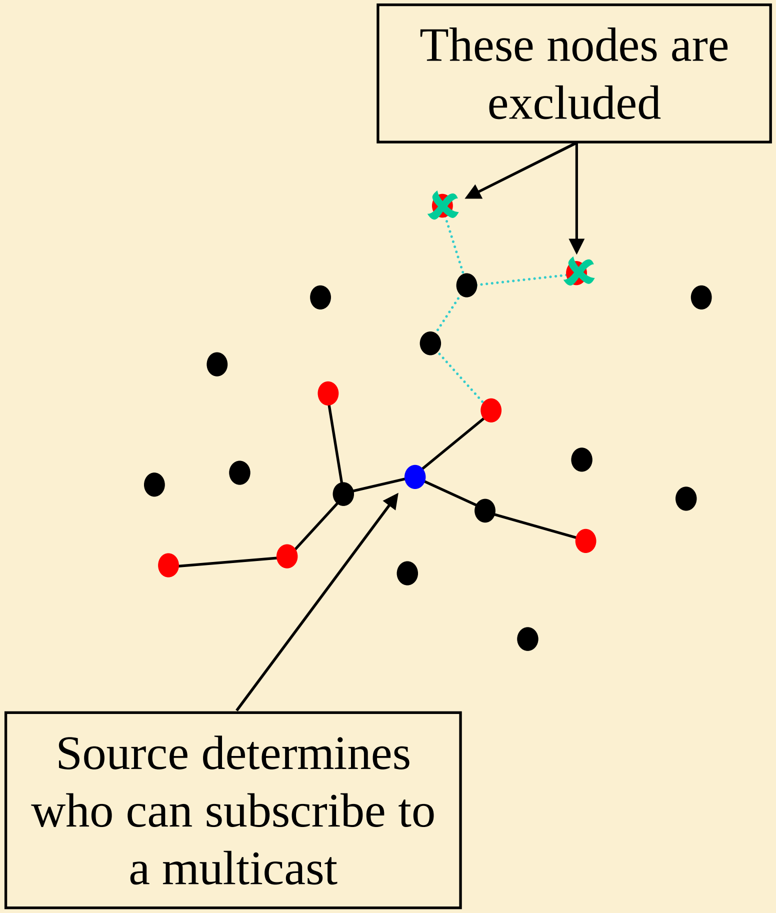


C. Murthy and B. Manoj, *Ad Hoc Wireless Networks: Architectures and Protocols*, Prentice Hall, Upper Saddle River, NJ 2004

- **Wireless multicast protocols build state at routers too!**
  - **Designed to react to membership changes (not topology)**
  - **Cannot control group membership**
- **Like routing there are proactive and reactive protocols**
- **Instantiation for each source/core - multicast group combination**
  - **A LOT of overhead**

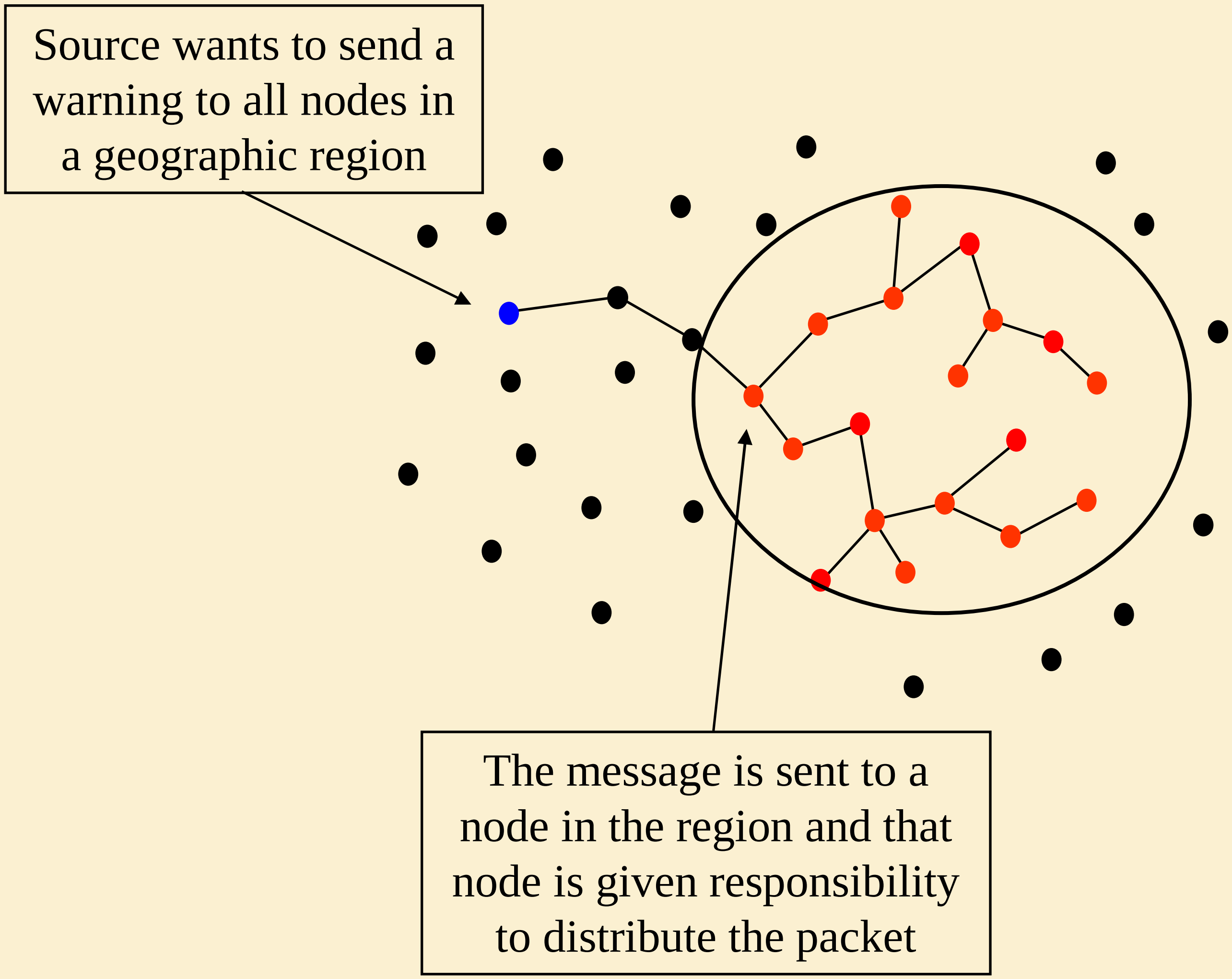
Application dependent multicasting scenario - controlled access

- Limiting distribution of multicast data to those nodes that have a need to know



Application dependent multicasting scenario - geographic warning

- A multicast is sent to all nodes in a geographic region



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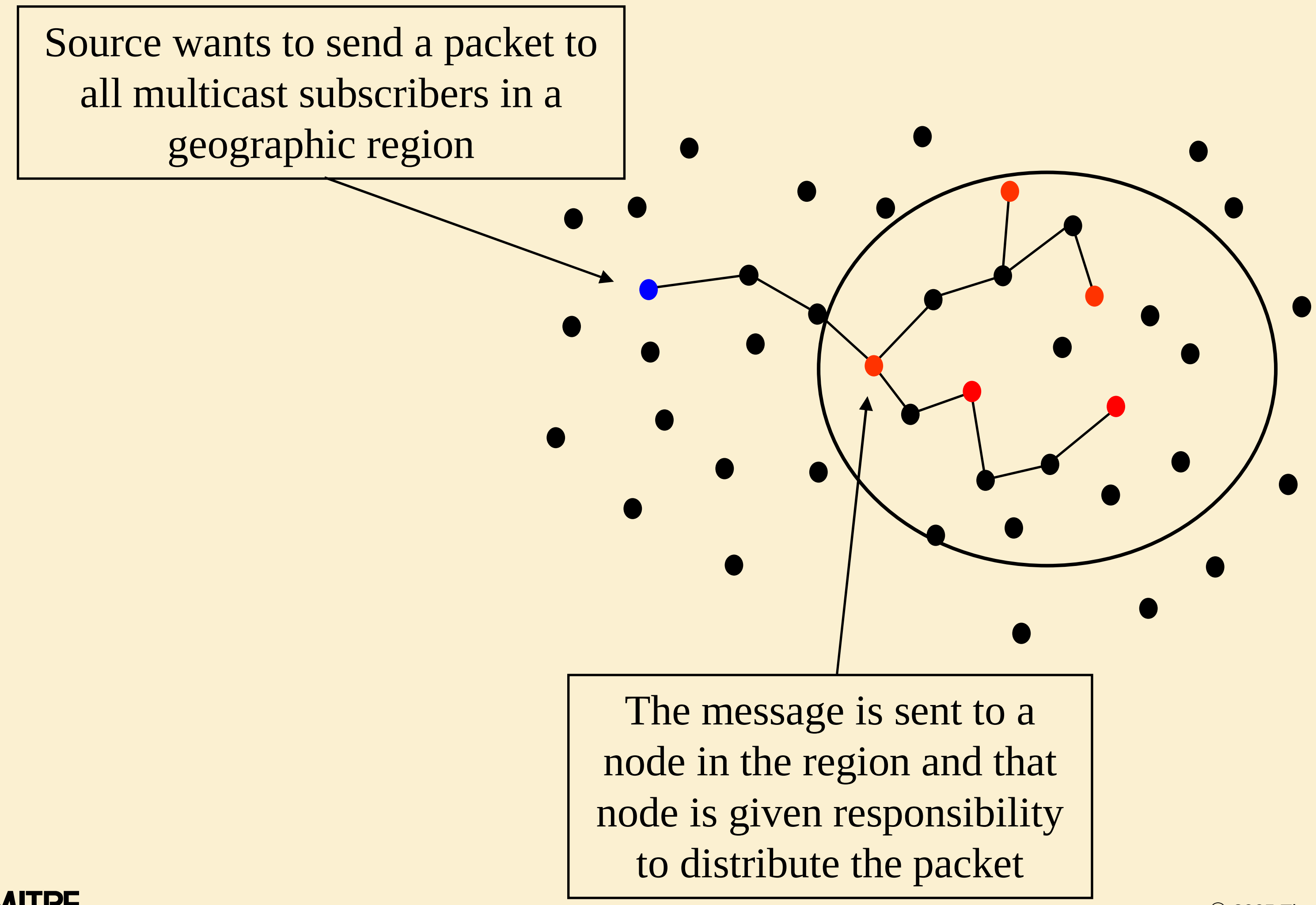
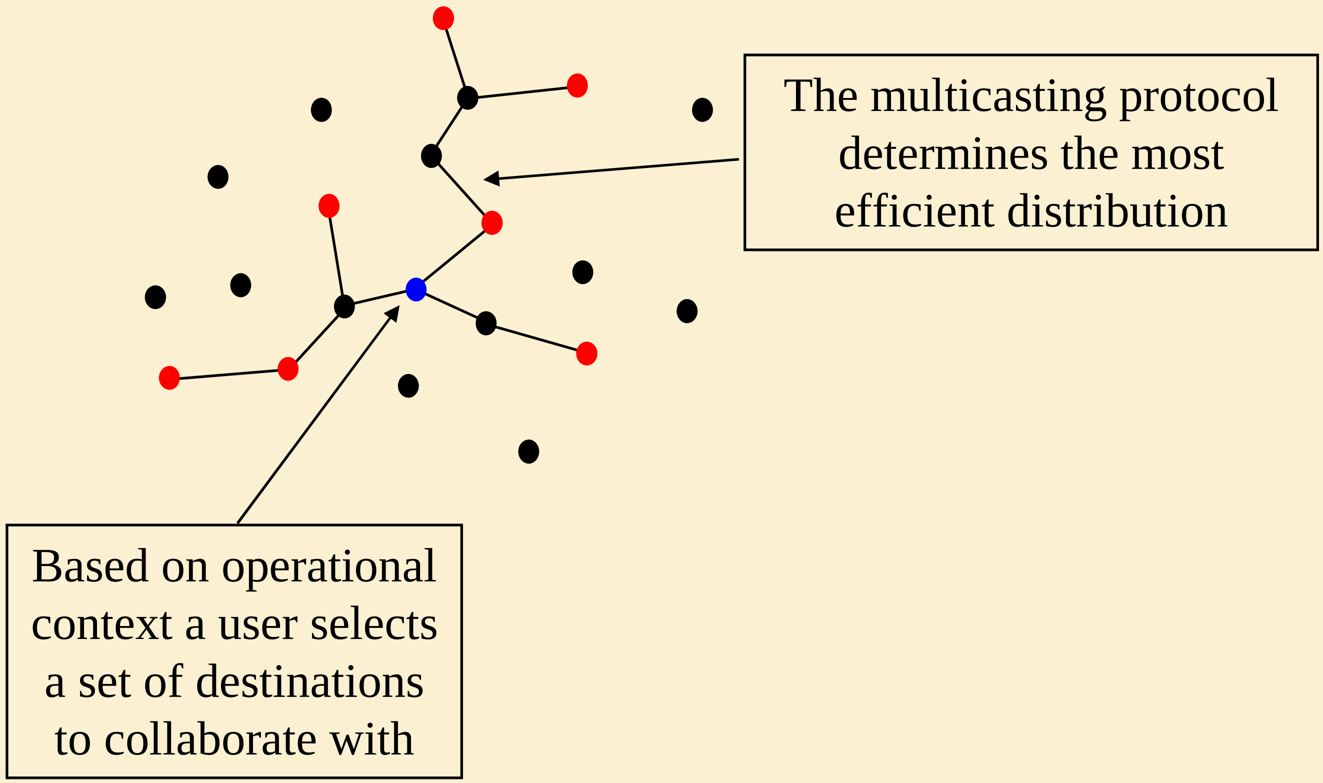
Application dependent multicasting scenario - geographic distribution

- A multicast is sent to all multicast subscribers in a geographic region



Application dependent multicasting scenario – ad hoc collaboration

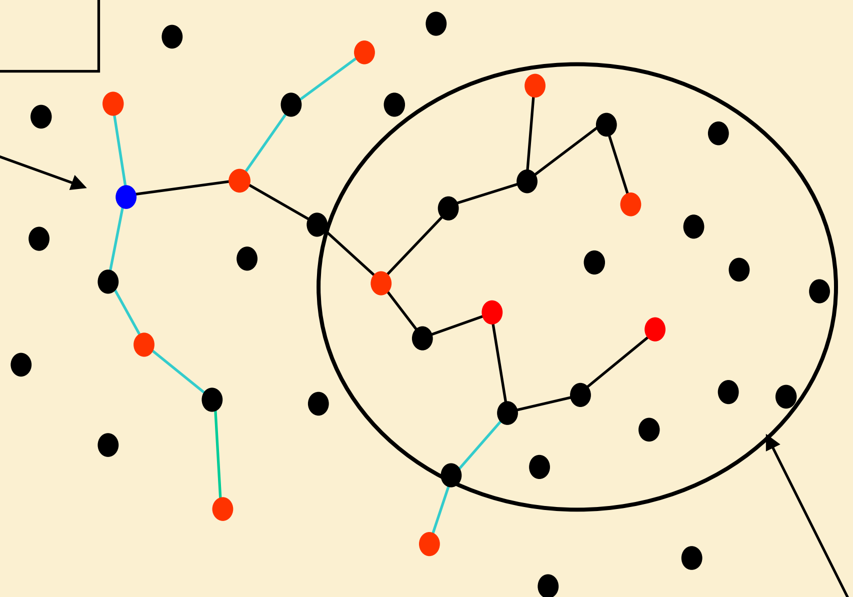
- A user or application selects a set of destinations to which it wants to multicast



Application dependent multicasting scenario - throttled dissemination

- **Members of multicast groups get periodic updates at different rates based on their context and need to know**

Multiple nodes subscribe to multicasts concerning a general topic (e.g enemy activity)



Updates on the topic are sent more frequently to destinations with a greater need to know (e.g. enemy activity to nodes in the same area of interest)

—— Links used every minute
—— Links used every 10 minutes

Segue

- We are not aware of any multicasting protocol other than Node State Multicasting (NSM) that supports both the standard and these application dependent multicast scenarios
- NSM achieves this capability without creating state and with little overhead that is not already a part of the accompanying Node State Routing protocol

Multicasting

- NSR support of multicasting
  - Node states provide a means for nodes to subscribe to multicast addresses
  - Explicit indication of subscribers to multicast addresses
  - Location information supports geographical multicast
  - Use of existing routing tables provides a SPT solution
- SCR MAC support of multicasting
  - Multiple packet formats for explicit multicasting

- Physical layer states

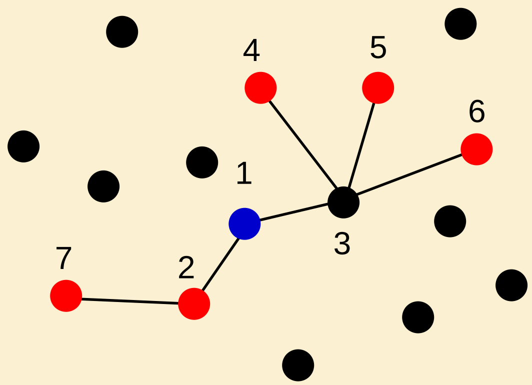
1-meter path loss	Location
Propagation map	Velocity
Antenna gain map	Direction
Spectrum usage map	Radio configuration

- MAC states

MAC address	Queue size
Peer-to-peer channel	CBR bitmap

- IP states
  - IP addresses
  - Network membership

Comparison of reliable and unreliable multicast



- Source
- Multicast destination

Packets sent with reliable multicast are peer-to-peer and are acknowledged while unreliable multicast packets are broadcasted and not acknowledged

Reliable Multicast

SRC - 1 NH - 2 DST – An MC address
MC DST List – 2, 7

SRC - 1 NH - 3 DST – An MC address
MC DST List – 4, 5, 6

SRC - 2 NH - 7 DST – An MC address
MC DST List – 7

SRC - 3 NH - 4 DST – An MC address
MC DST List – 4

SRC - 3 NH - 6 DST – An MC address
MC DST List – 6

SRC - 3 NH - 5 DST – An MC address
MC DST List – 5

Unreliable Multicast

SRC - 1 NH - -1 DST – A MC address
DST List – 2, 2, 7, -1, 3, 4, 5, 6

SRC - 2 NH - -1 DST – A MC address
MC DST List – 7, 7

SRC - 3 NH - -1 DST – A MC address
MC DST List – 4, 4, -1, 5, 5, -1, 6, 6

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Geographical multicasting strategies

- **Standard header**

SRC Addr	NH Addr	DST Addr	MC Qualifier

SRC Addr – The node transmitting the packet
NH Addr – The next hop destination of the packet
DST Addr – The destination node that subsequently multicasts the packet
MC Qualifier – Method use to identify the final destinations, 0 = none, 1 = DST list, 2 = MC or broadcast addr, 3 = State values

- **Special multicast headers**

DST List

Final destinations are those in the list

Broadcast Addr	Region description

Final destinations are all nodes in the region

MC Addr	Region description

Final destinations are all nodes in the region that subscribe to the specified multicast address

State values	Region description

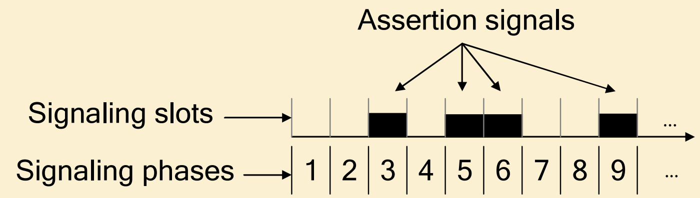
Final destinations are all nodes in the region that have state values that match the listed values

NSR Topics

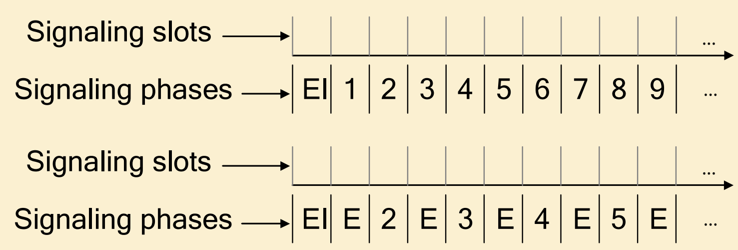
MITRE

Differentiating primary and secondary access

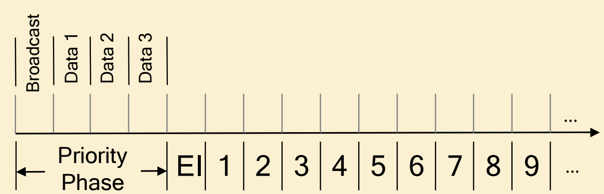
- Signaling design options
  - Simple design



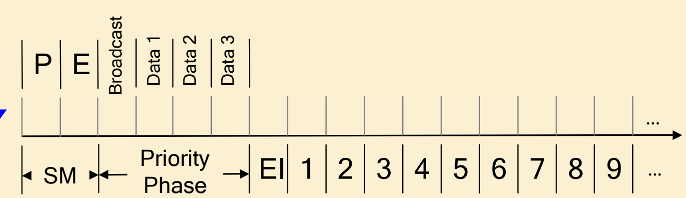
  - Extending the range for two hops



  - Prioritized access



  - Differentiating primary and secondary use



DEMONSTRATION

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Spectrum Management

- SCR & NSR functionality that supports spectrum management
  - Node state dissemination mechanism supports distributing
    - Observations of spectrum use (*Every node is a detector*)
    - Propagation properties and node locations necessary to make spectrum assignment decisions
  - Channelization scheme that enables destinations to receive peer-to-peer packets on separate channels

- Underlying ad hoc network can support spectrum assignment to other networks

Node states

- **Physical layer states**

  1-meter path loss — **Location** — **Spectrum usage map**
  Propagation map — **Velocity** — **Node configuration (# radios)**
  Antenna gain map — **Direction** — **Radio channels**

- **MAC states**

  MAC address — **Queue size**
  Peer-to-peer channel — **CBR bitmap**

- **IP states**

  IP addresses
  Network membership (for multiple radios)

- **Energy states***

  Energy reserve — **Dozing period**
  Dozing state — **Receive fraction**
  Dozing offset

- **Services**

  Infrastructure status
  Service subscription

- **Administrative**

  Timestamp
  Cost to use the routing construct

*J.A. Stine and G. de Veciana, "A comprehensive energy conservation solution for mobile ad hoc networks," *IEEE Int. Communications Conf.*, 2002, pp. 3341 - 3345.

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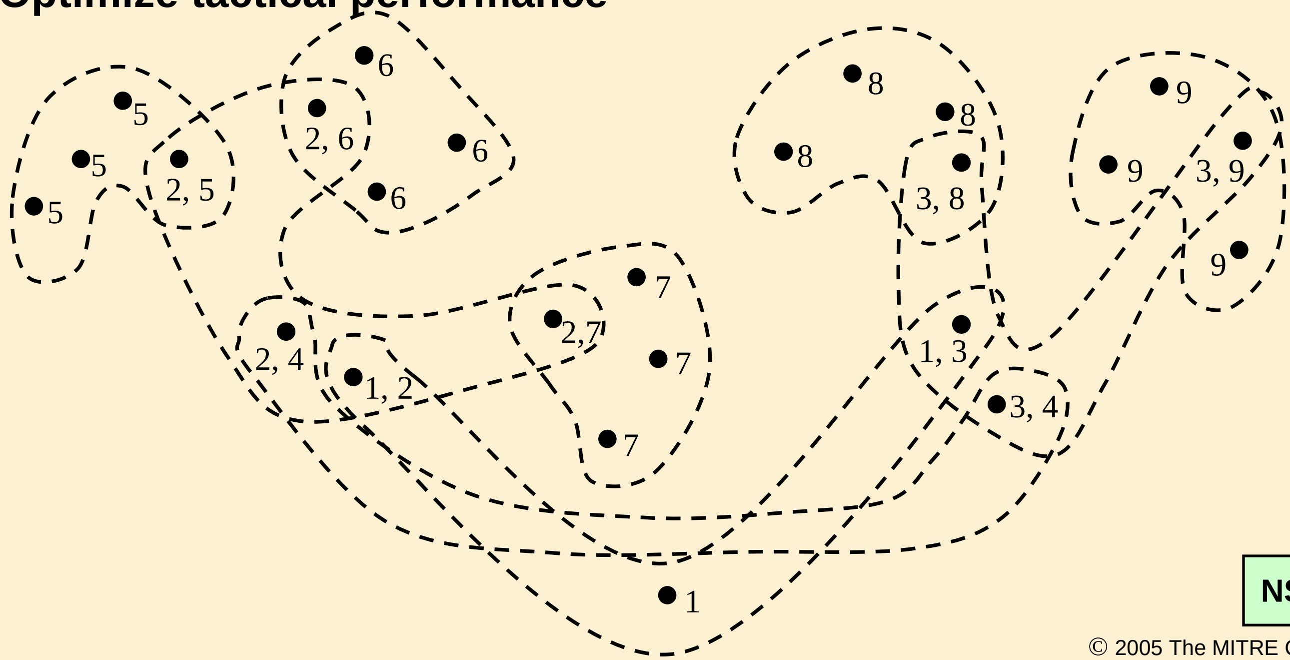
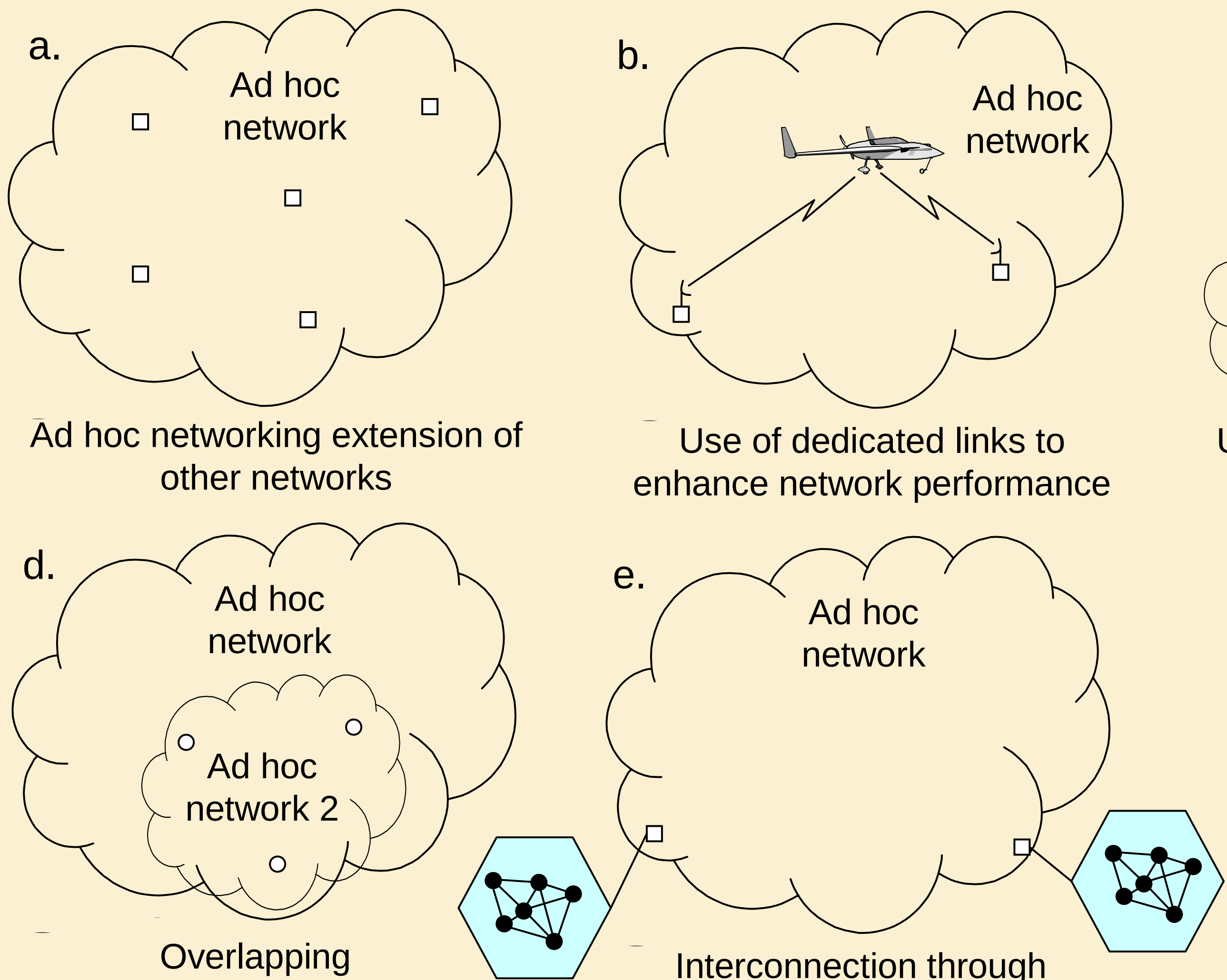
Spectrum management - 2

- Assumes nodes have multiple radios
  - One is part of the ubiquitous ad hoc network
  - Others may be voice and unit multicast nets and radios for long range point-to-point links
- Assumes network is aware of available spectrum
- Spectrum manager assigns spectrum (possibly waveform) to
  - Achieve spatial reuse
  - Optimize tactical performance



NSR Topics

Heterogeneous network architectures



a. Ad hoc networking extension of other networks

b. Use of dedicated links to enhance network performance

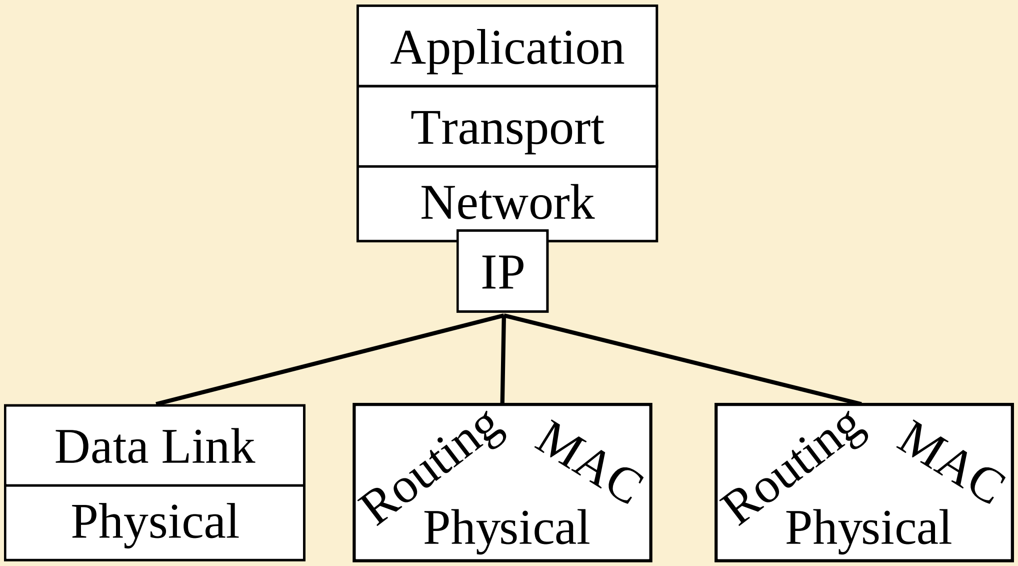
c. Use of dedicated links to connect a partitioned ad hoc network

d. Overlapping ad hoc networks

e. Interconnection through an ad hoc network

- □ Access points to externally connected nodes
- Dedicated link connection, e.g. satellite, UAV, laser, and cable connections
- ○ Nodes that participate in multiple ad hoc networks

Heterogeneous node



NSR Topics

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