

Directional Antenna Systems for Ad Hoc Networks

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Tutorial Presentation

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Roadmap

- Part 1: Overview: Why Directional Antenna systems?
- Part 2: Directional Antenna Fundamentals
- Part 3: Medium Access and Routing

20 minute break

- Part 4: Modeling and Simulation for Ad Hoc Networks with Directional Antenna systems
- Part 5: System design, prototype and experiences

Part 1

Why Directional Antennas?

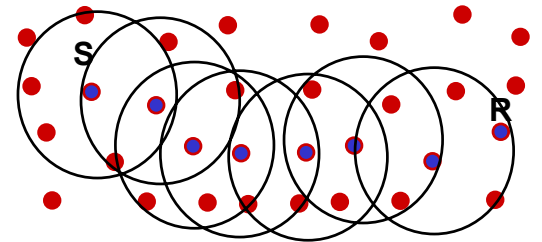
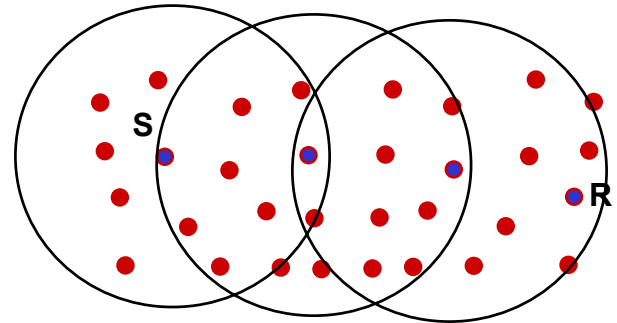
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Motivation

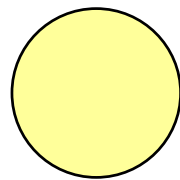
The capacity problem in ad hoc networks

- The wireless channel is a shared one
- Transmission along a single multihop path inhibits a large number of nodes
- Shorter hops help, but only to a certain extent
- Gupta-Kumar capacity result
 - $T = \Theta(W/\sqrt{n \cdot \log n})$
- A major culprit is omnidirectionality!

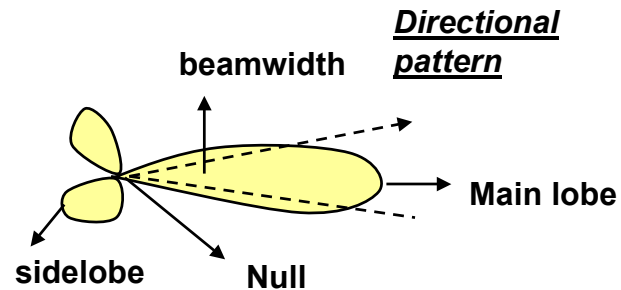


Directional Antennas

- A directional/beamforming antenna has certain preferred transmit and receive directions
 - *Gain* measures the relative power in one direction compared to an isotropic antenna

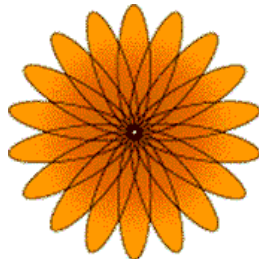


Isotropic pattern



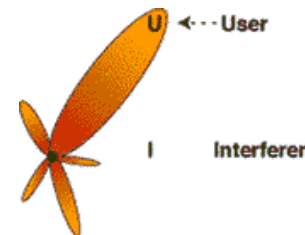
- Steerable beam vs switched beam

Switched beam



“Beamforming matrix”

Steered beam

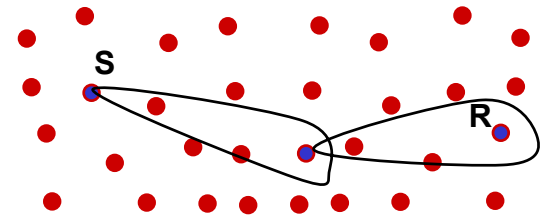


“Smart antennas”
“Adaptive arrays”
“Phased arrays”
“MIMO”

Benefits of directional communications

■ Directional Communications

- Less energy in the wrong directions
 - Better spatial reuse
 - Less multipath
- More energy in the right directions
 - Longer ranges
 - More robust links



■ Both higher spatial reuse and longer ranges can be simultaneously obtained

- Not an “either or”

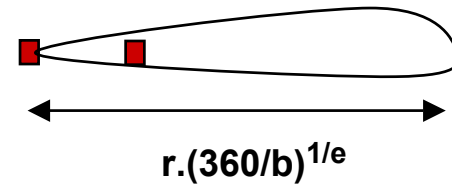
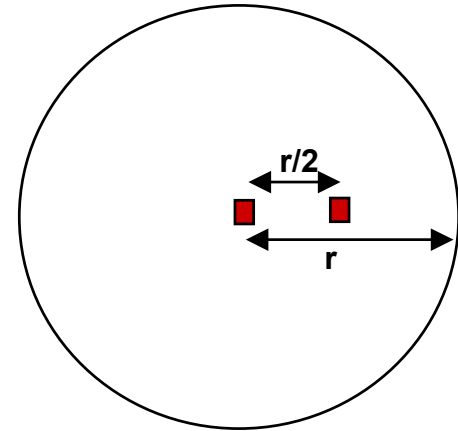
Benefits(2)

- Spatial reuse implies higher aggregate capacity
- Longer ranges imply lower end-to-end latency
- Higher SINR, longer ranges imply better connectivity
- Better tolerance to jamming due to “nulling” capability
- Narrower beamwidth implies better security from interceptions

A closer look at range improvement

A very rough calculation

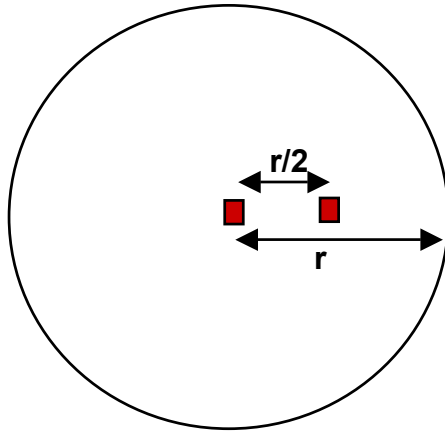
- Suppose that all of the power were to be directed within a beamwidth of b
- Let d be the directional range, P be the transmit power
- $P.k/r^e = (360/b).P.k/d$
- $d = r.(360/b)^{1/e}$
- For $b = 10$ deg, and $e = 4$,
 $d = 2.45r$



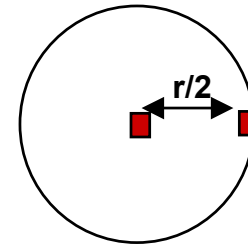
A closer look at spatial reuse improvement

A very rough calculation

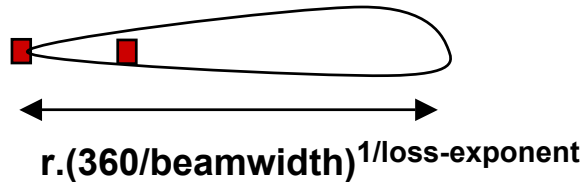
Area $\approx A$



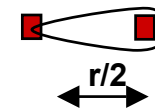
Area $\approx A/4$



Area $\approx A/6$ (for 10 deg bw, r^4 pathloss)



Area $\approx A/144$ (for 10 deg bw)



The full potential of Directional Antennas can only be exploited with transmit power control

Practical relevance

- Question: Aren't directional antennas too expensive/big for ad hoc networks?

- Directional antenna “simple” classification
 - Switched beam: Can select one from a set of predefined beams/directions
 - Steerable/Steered beam: Can point in almost any direction

- Size depends on frequency and number of elements
 - Radius of a k element cylindrical array = $c.k / 4.\pi.f$
 - c = speed of light, k = number of elements, f = frequency

- Cost depends on size and sophistication (“adaptivity”)
 - More adaptive it is, more expensive it gets, but better performance

Practical relevance(2)

■ Military

- Size of platforms (tanks, airplanes) can accommodate large array antennas
- These things cost a fortune anyway

■ Commercial outdoor using desktops/laptops

- For fixed ad hoc “mesh” networks
- Switched antenna sufficient, can be made cheaply and small

■ Commercial indoor using PDAs/wearables

- At higher frequencies, becomes realistic
- Radius of 8 element cylindrical array
 - at 5.8 GHz it is 3.3 cm, at 24 GHz it is 0.8 cm

Performance Potential

A broad (but brief) simulation study

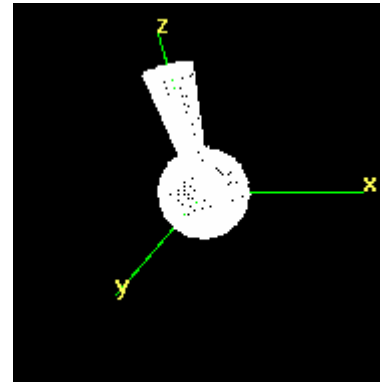
Simulation System

■ Simulation in OPNET v 6.0

■ Beamforming

- 4 semi-realistic gain patterns
- Transmit only
- Switched and steered
- Power control

Main lobe 20 dBi, side lobe -6.5 dBi,
beamwidth 20 degrees



■ Simulation parameters

- 40 nodes, random stationary network, 1.6 Mbps, r^4 pathloss
- 20 streams (random), Poisson traffic, 30 pkt buffer
 - Due to buffering, performance differences show up in “delay”
- Varying densities, gains

Protocol Models

- Emphasis is on estimating *relative* improvement in performance over omni-directional antennas
 - Abstract modeling of things that likely “cancel out”

- Channel Access
 - Very simple directional CSMA/CA
 - Aggressive: NAV not used
 - Conservative: NAV used as in omni

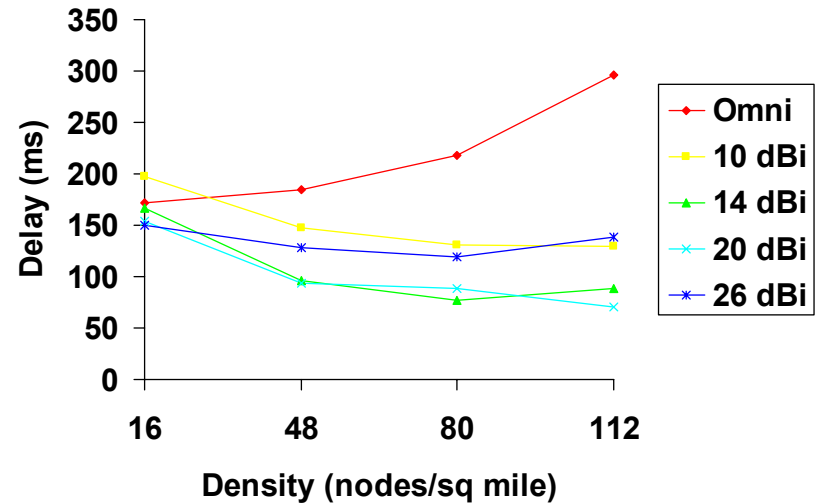
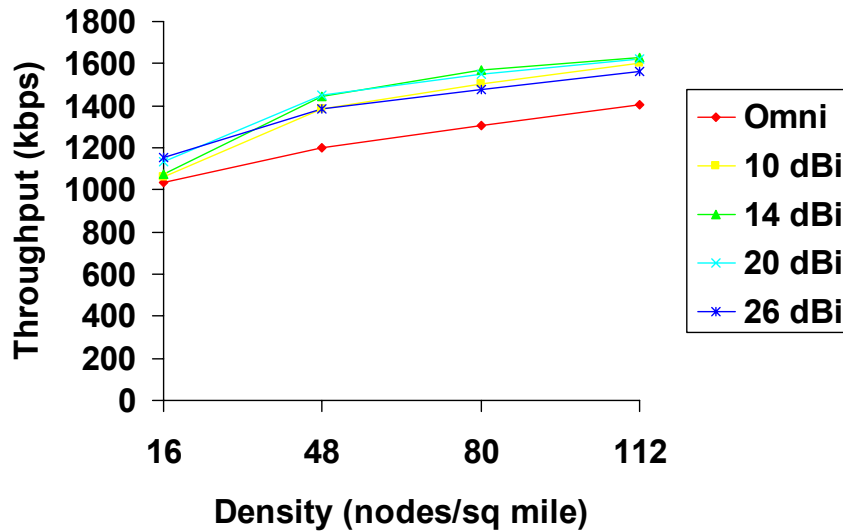
- Routing: Hazy-sighted link state (closest IETF MANET protocol is OLSR)

- Neighbor discovery
 - Omni-neighbors only (range advantage not exploited)
 - Directional neighbors (range advantage exploited)

Performance (1)

Aggressive D-MAC, Steered beams, omni neighbors only, no power control

Slight improvement in both throughput and delay over omni but nothing exciting. Increasing gain does not really increase performance.

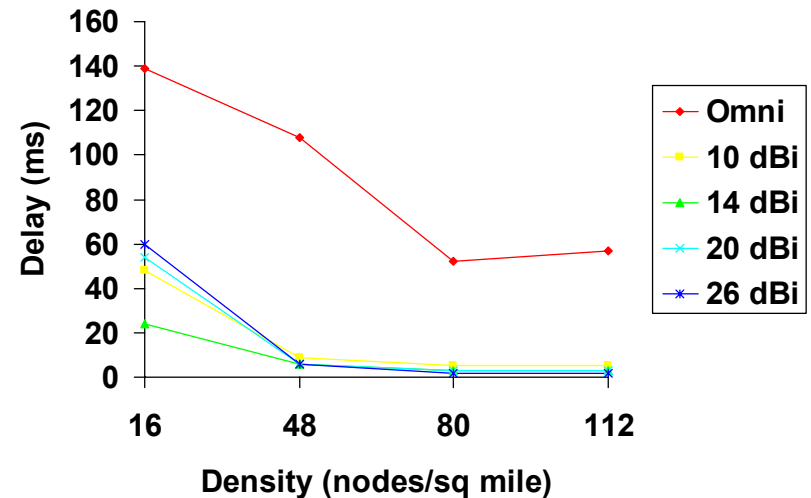
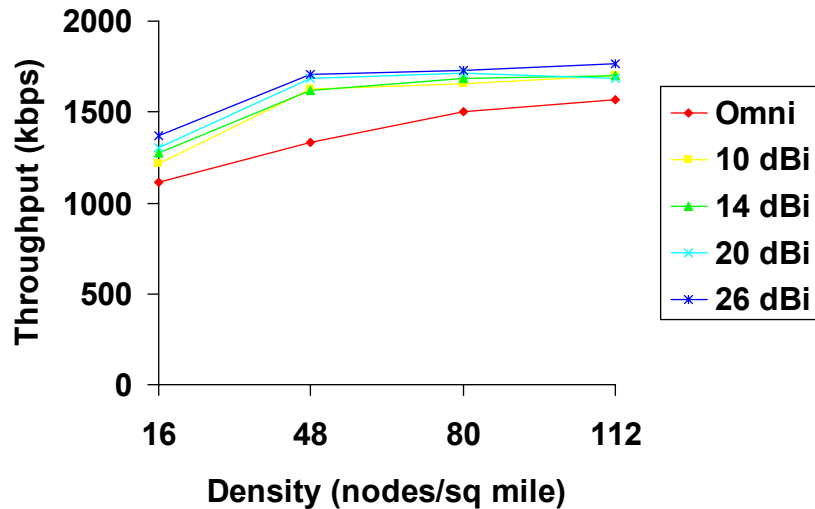


Performance with power control

Aggressive D-MAC, Steered beams, omni neighbors only, power control

**Throughput improvement of up to 28 % (26 dBi, density 48),
delay improvement of up to a factor of 26 (26 dBi, density 112) !!**

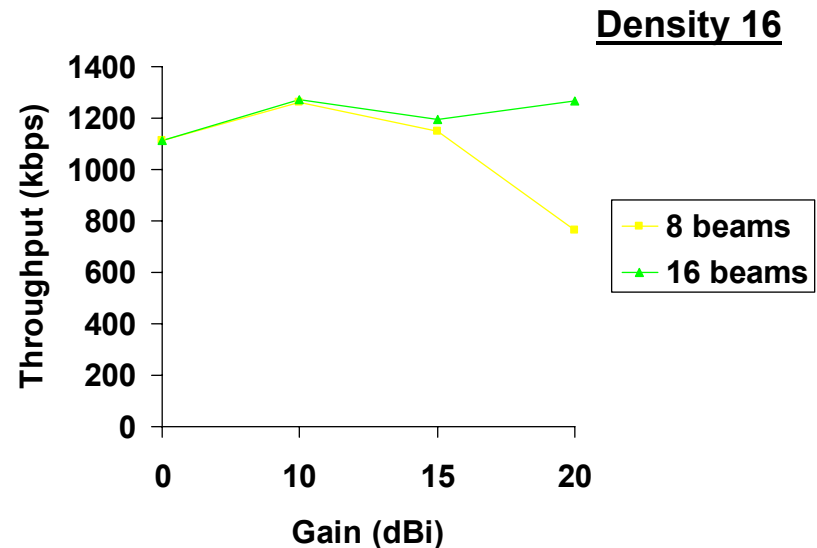
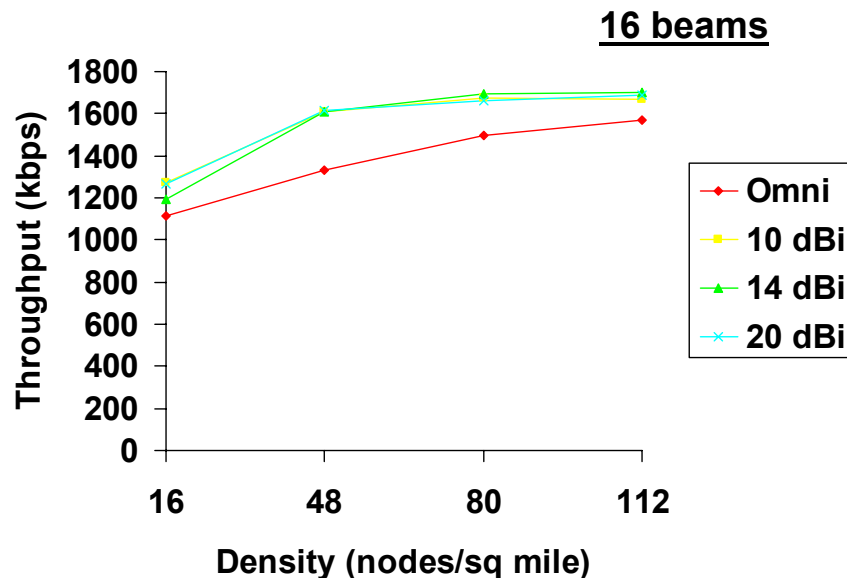
So unless we have power control, the full potential cannot be harnessed



Switched instead of Steered

Aggressive D-MAC, Switched beams, omni neighbors only, power control

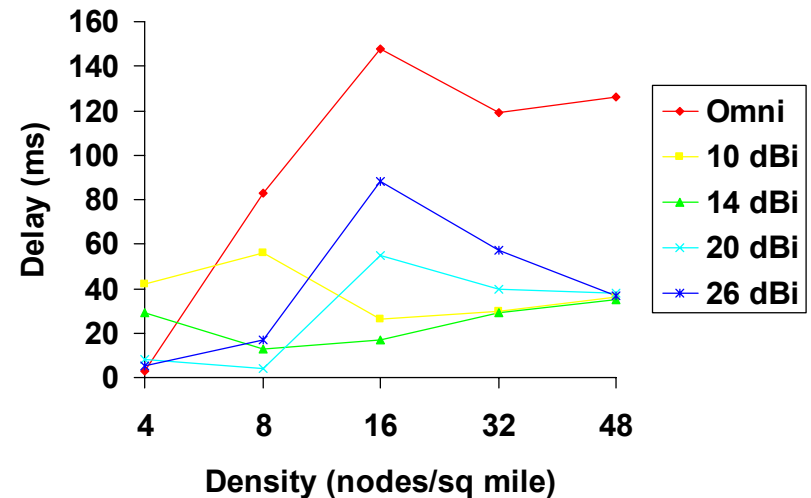
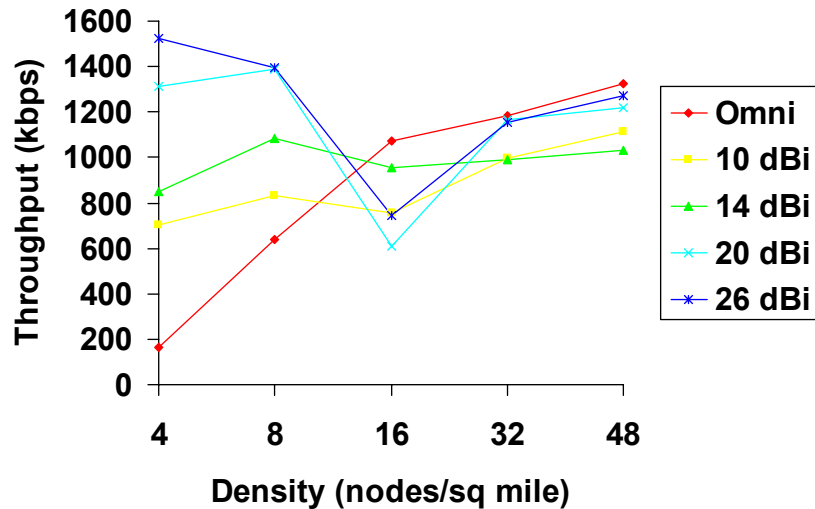
Switched beam performance is similar to steered beam performance, as long as adequate number of beams are present (coverage)



Effect of longer range

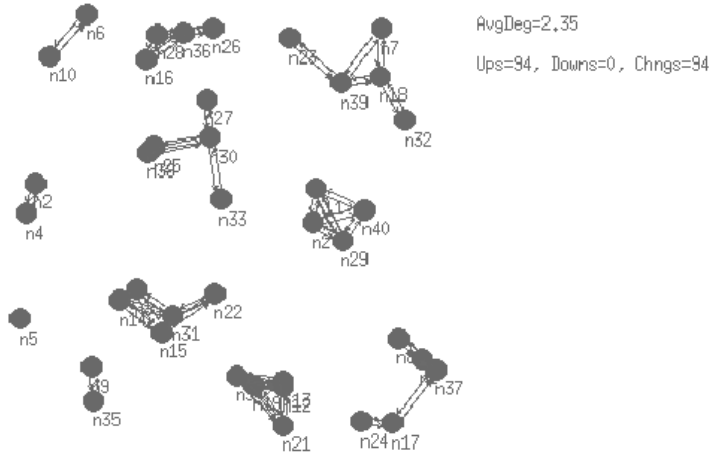
Aggressive D-MAC, 12 Switched beams, directional neighbors, power control

A huge advantage at lower densities (prevents partitioning)
Need smarter routing than shortest path at higher densities

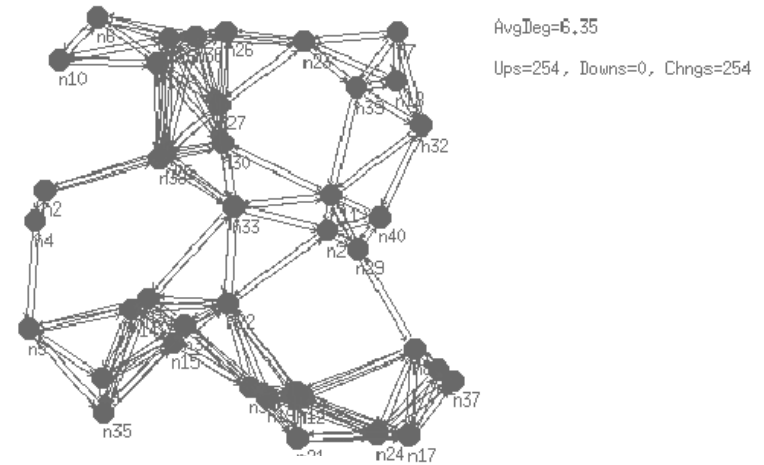


Directional Links and Connectivity

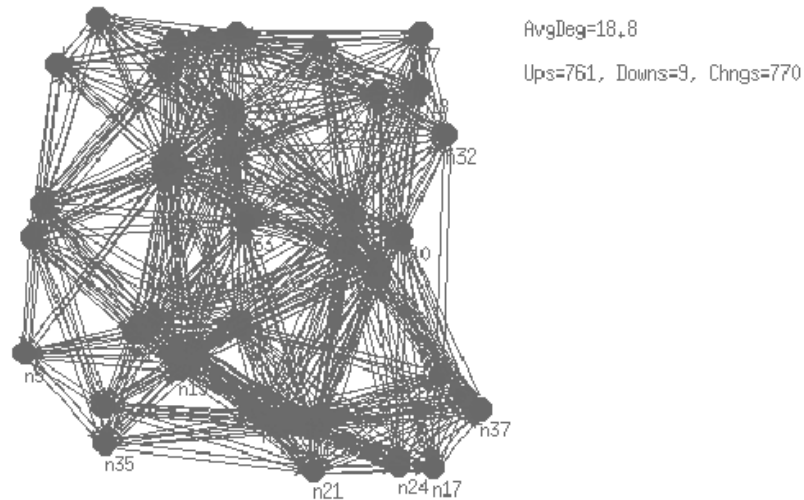
0 dBi (omni) connectivity



10 dBi sw/beam connectivity



20 dBi sw/beam connectivity



The Beamwidth vs Connectivity Tradeoff

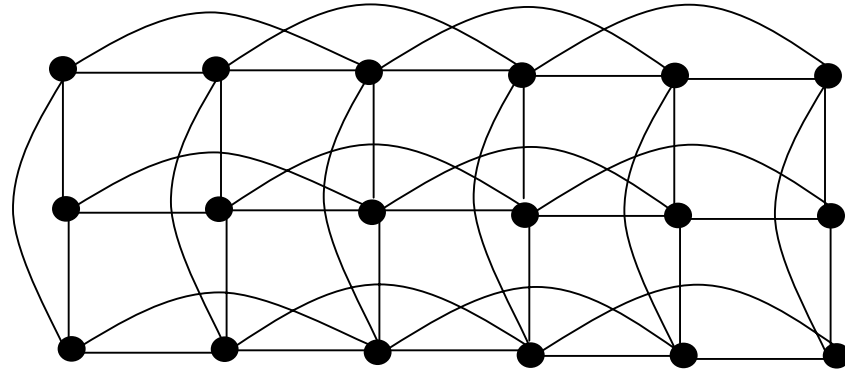
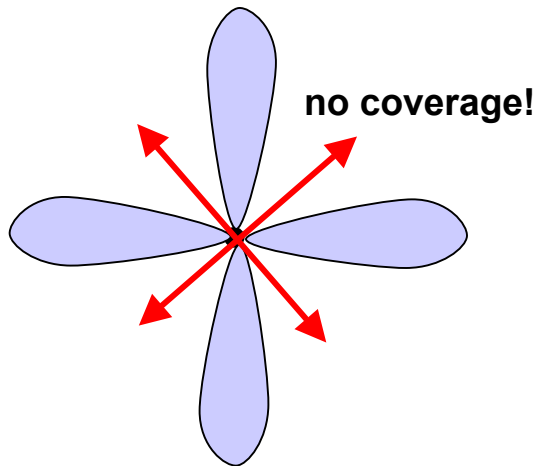
Unique to Switched Beam Systems

- Given a fixed number of switched beams, how does the performance depend upon the gain (beamwidth)?

- Informally, *coverage* $\approx B \cdot N / 360$
 - B = beamwidth in degrees; N = Number of beams
 - Coverage < 1 means there are “blind” spots in the directional antenna system
 - With 4 beams B has to be at least 90 degrees for coverage > 1

Beamwidth vs Connectivity (2)

- Increasing the gain increases range and spatial reuse, but also increases the blind spots



- *What is the optimal value of gain?*

Part 1 Concluding Remarks

- Directional Antennas have tremendous potential for ad hoc networks and have timely relevance

- How can we harness this potential?
 - We need the ability to *control* the directional antenna system from the higher layers

- So we need to understand
 - How directional antennas work and how to model them
 - What changes are needed at the MAC and Network layers to perform the required control of directional antennas
 - How can these changes work cohesively as a system

- Stand by to find out..... !