Wireless Mesh Networking

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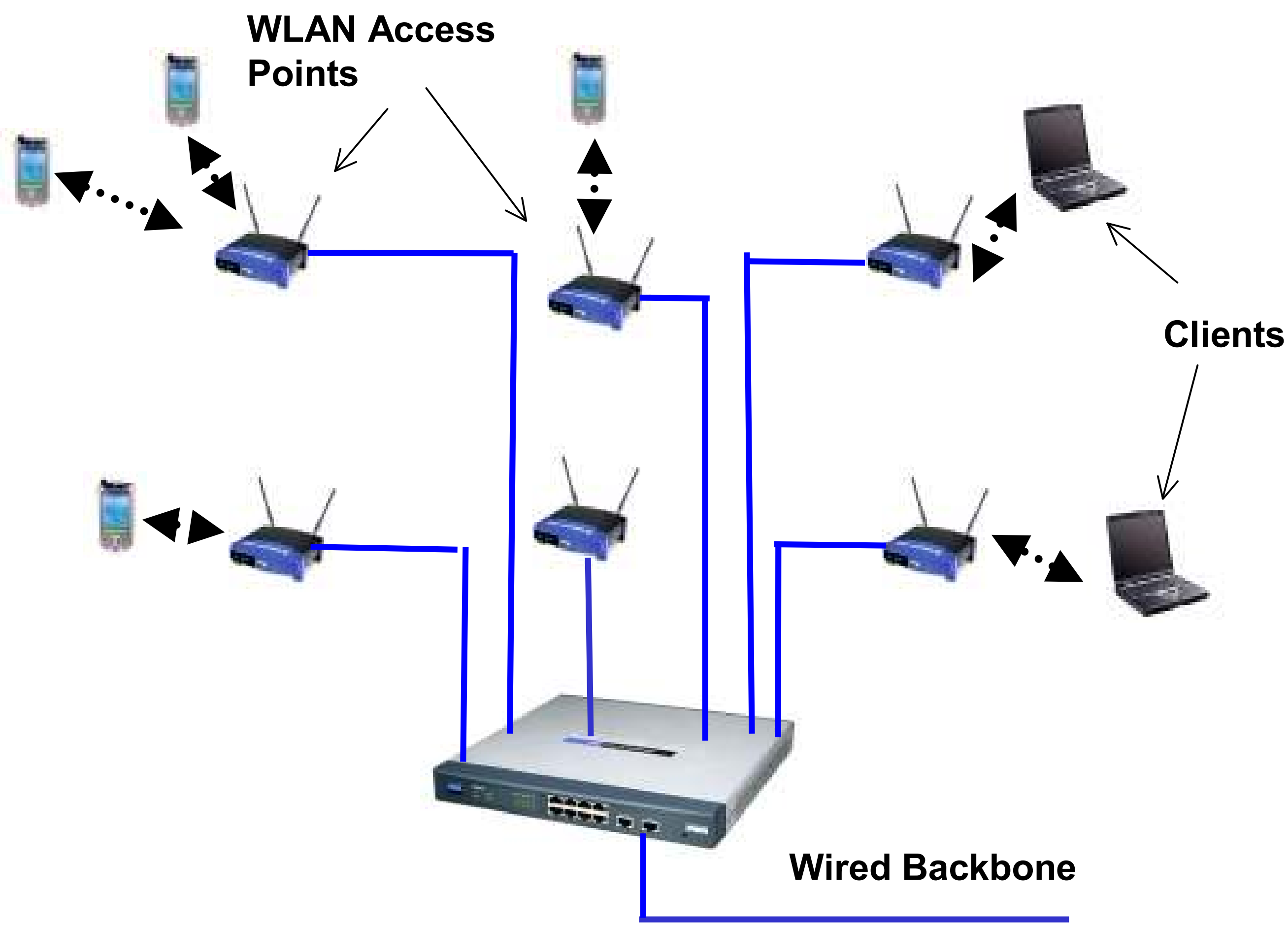
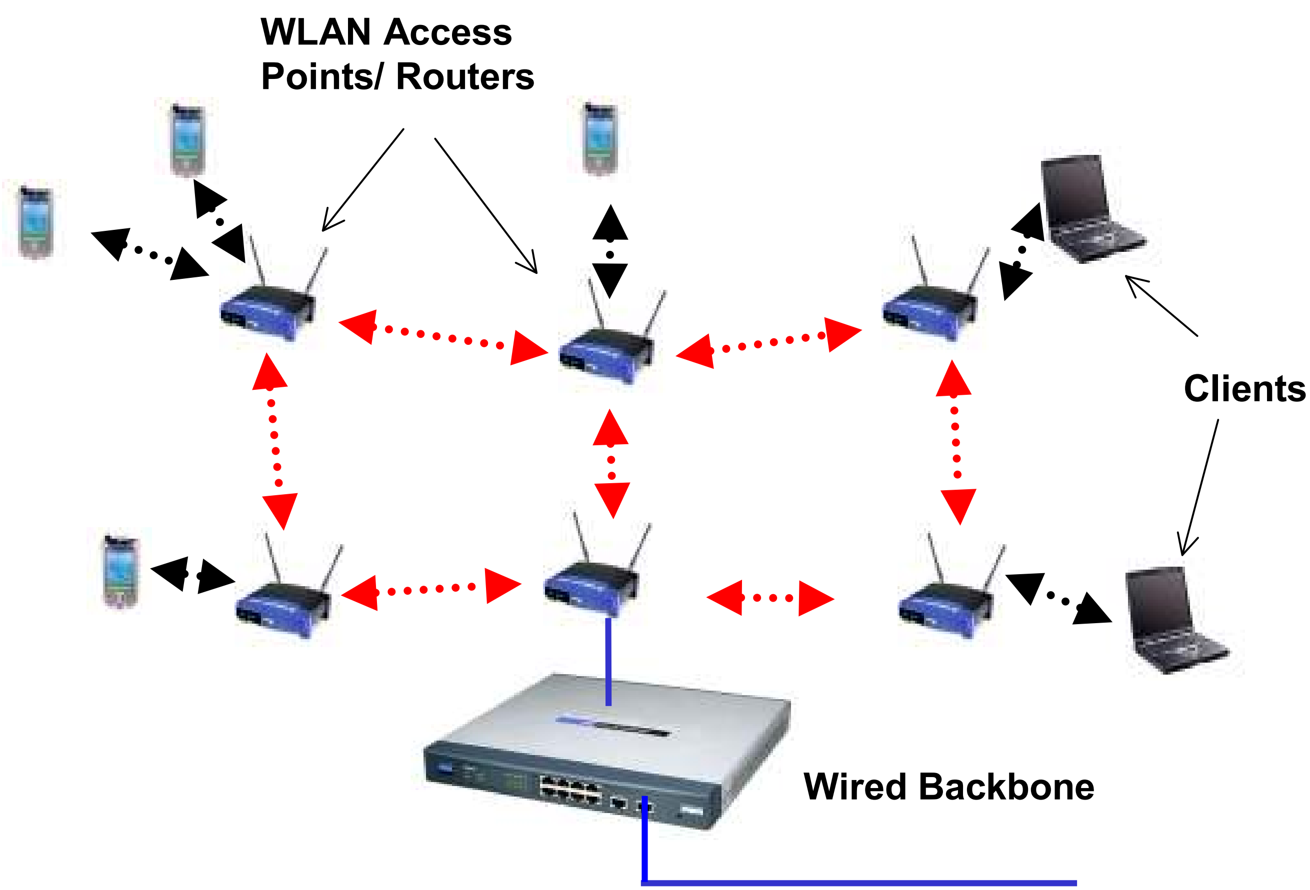
The Wireless Paradox

What is a Mesh Network?



- "Wireless Paradox" : WLAN Access Points are typically wired.

What is a Mesh Network?



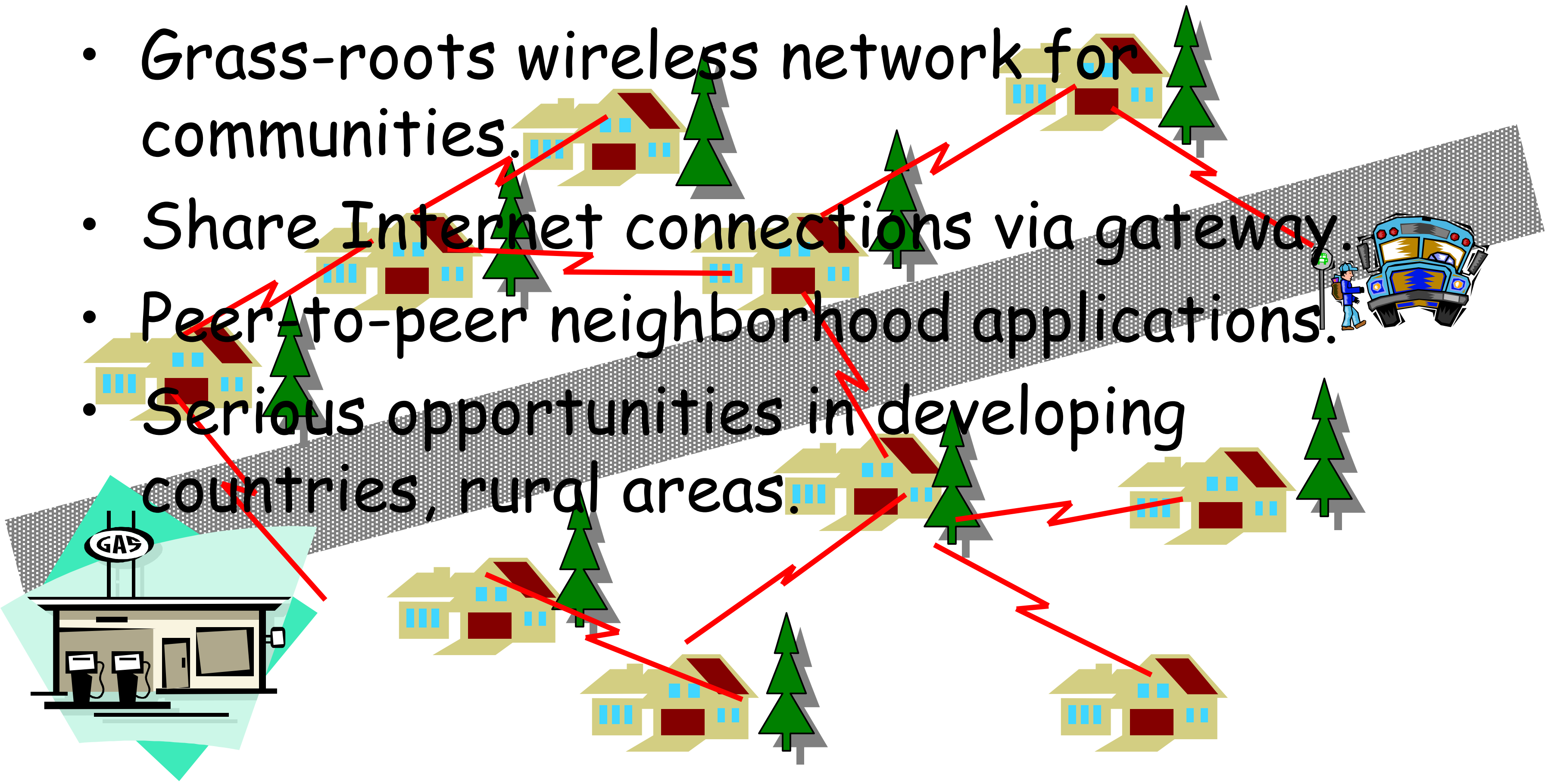
- Get rid of the wires from wireless LAN.
- Access Points double as "wireless routers."
- Wireless routers form a backbone network.

Mesh Networking Advantage

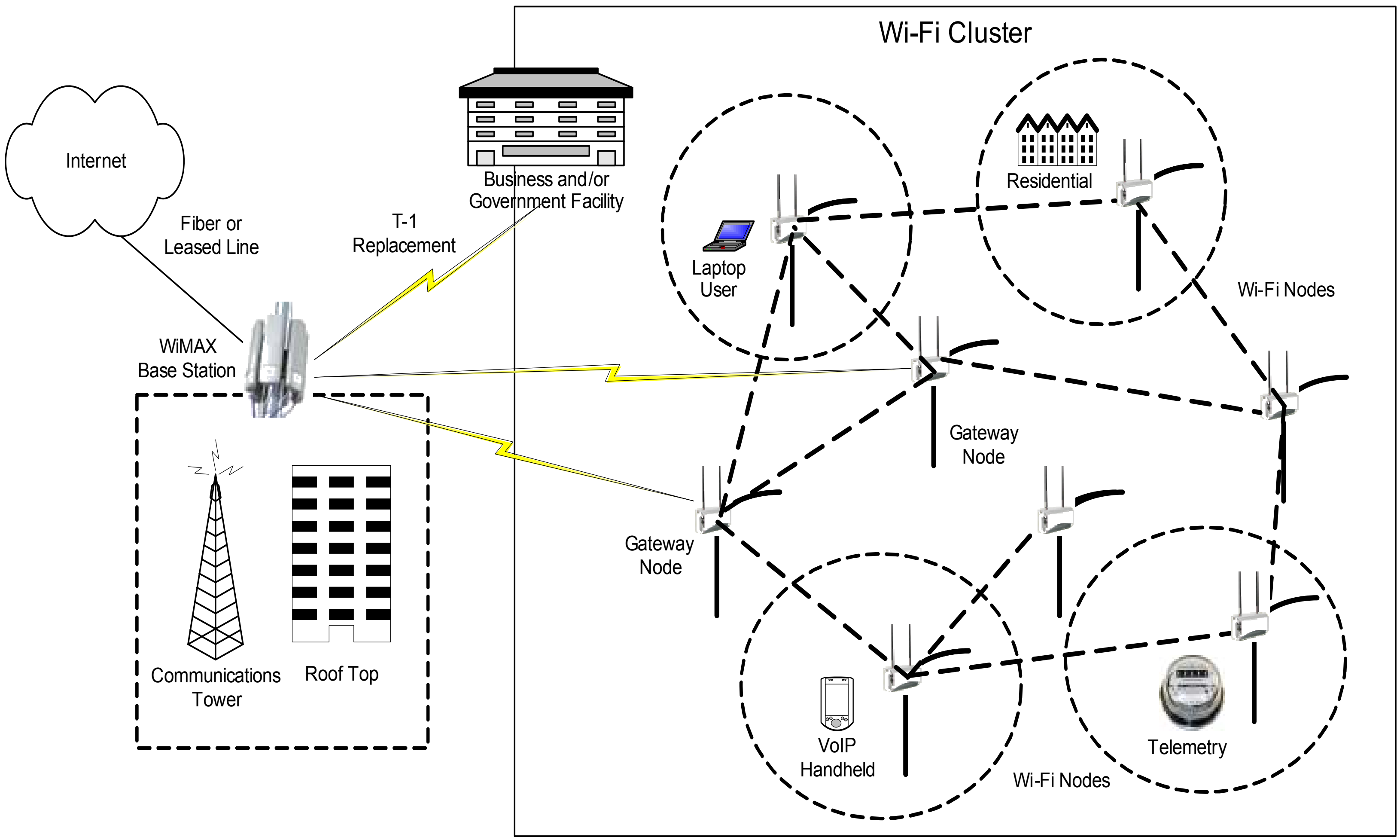
- Very low installation and maintenance cost.
  - No wiring! Wiring is always expensive/labor intensive, time consuming, inflexible.
- Easy to provide coverage in outdoors and hard-to-wire areas.
  - Ubiquitous access.
- Rapid deployment.
- Self-healing, resilient, extensible.

Community Mesh Network

- Grass-roots wireless network for communities.
- Share Internet connections via gateway.
- Peer-to-peer neighborhood applications.
- Serious opportunities in developing countries, rural areas.



Wireless Philadelphia



[Source: City of Philadelphia, Mayor's Office of Information Services www.wirelessphiladelphia.org]

The Cloud at *Wireless* Philadelphia

MyCloud | What is the Cloud? | Help

Welcome to the Cloud

Log in for customized content in Love Park and FREE wireless internet access from Wireless Philadelphia.

Email Address: Password: Log In

The Cloud is the new way to access Wireless Philadelphia, SSID: wifiphilly

For everyone who lives, works, and plays on the Parkway

The Cloud at Wireless Philadelphia is your way to use wireless internet and more throughout the Parkway from Love Square to the Museum of Art. The Cloud makes Wireless Philadelphia about more than just access. It makes Wireless Philadelphia about convenience, content and community connections.

Learn more about The Cloud.

This Month's Featured Opportunity

Salvador Dali @ The Museum of Art

Salvador Dali is one of the most famous painters of the 20th century. Philadelphia is the only city in the country to host his centennial celebration. Experience his hallucinating vision, intense creativity, and consummate showmanship at the Museum of Art.

Create an account!

Get FREE access to the internet with a Wireless Philadelphia account.

New User Step 1 of 4: Email / Login

Email: Next

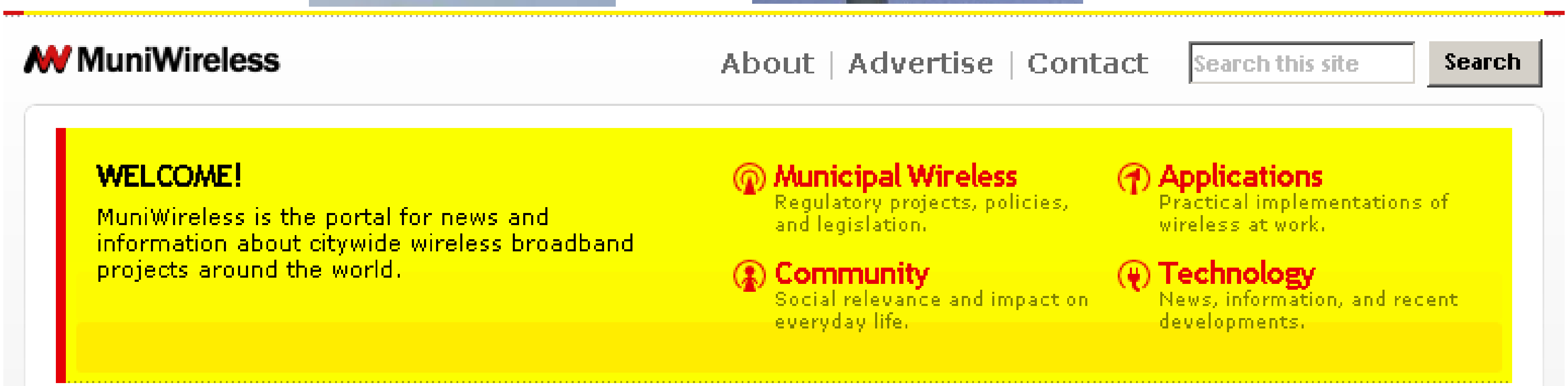
(e.g. name@example.com)

I want my Wireless Philadelphia!

"I heard that Love Park is the place to try Wireless Philadelphia. I just got my laptop and wanted to do homework outside since it is such a beautiful day. I can't wait for the whole city to be wireless!" - student, Temple University

Metro-Scale Mesh Network

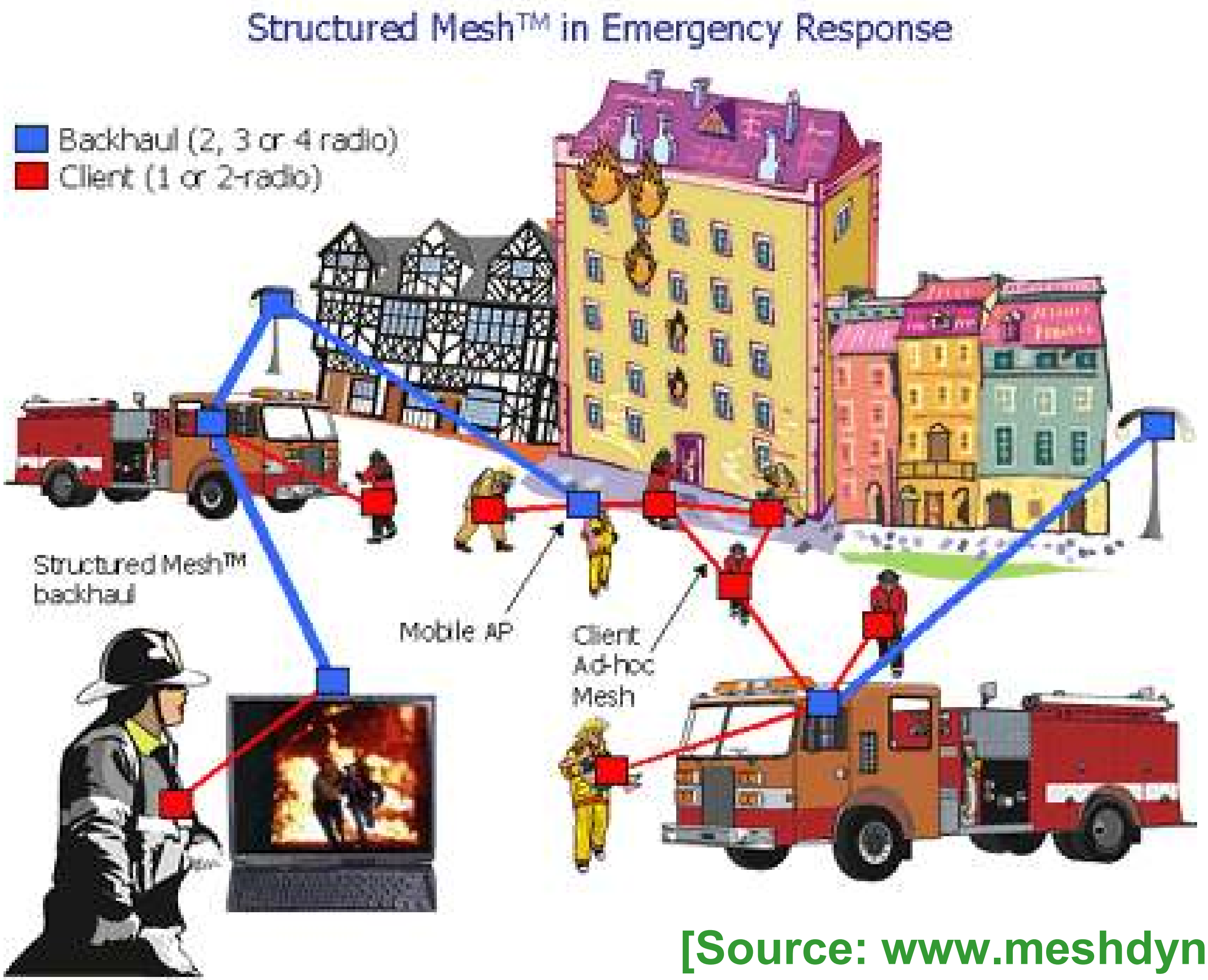
Photo Credit:
Mesh Dynamics



[Source: http://muniwireless.com]

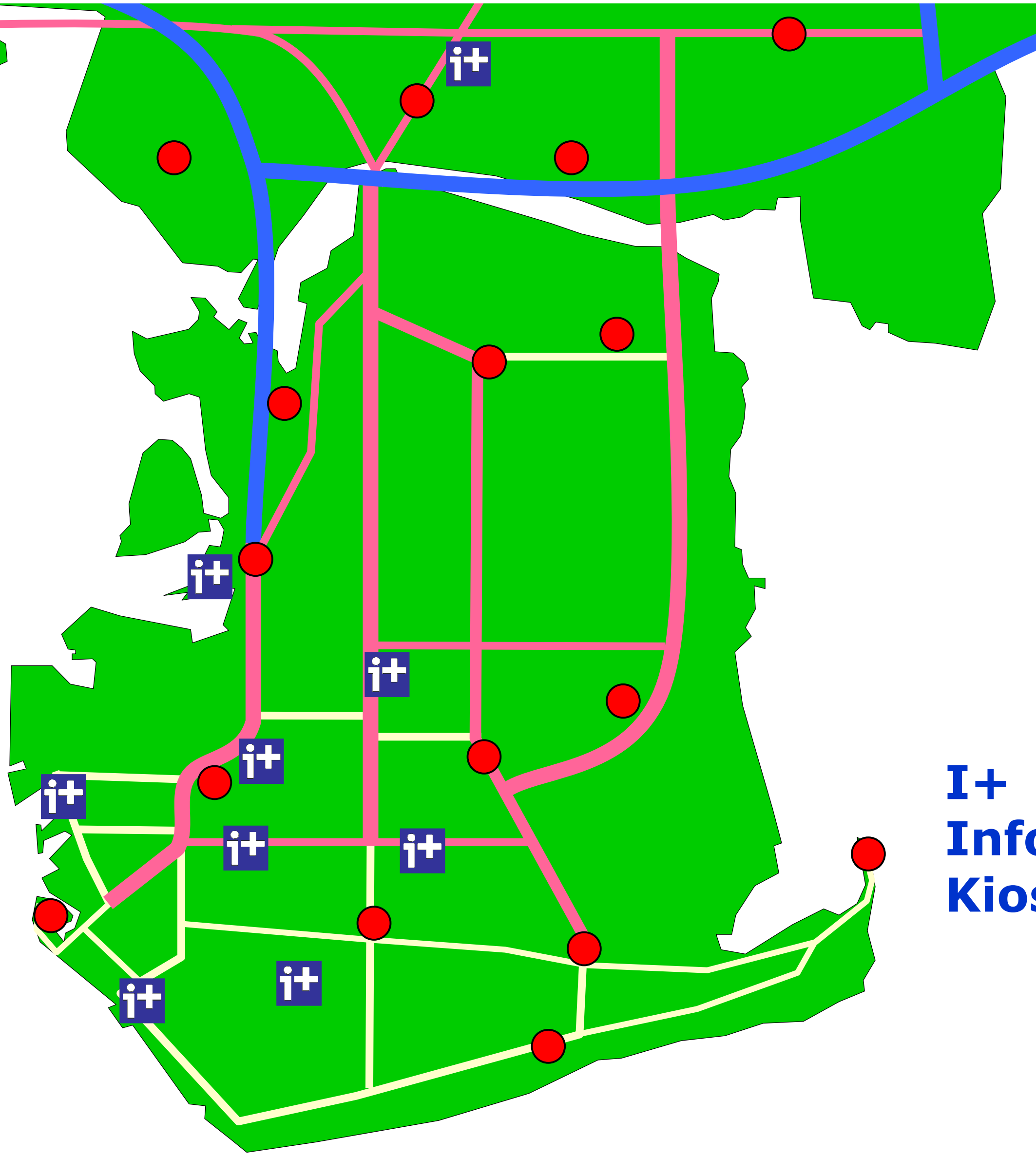
- Covers an entire metropolitan area.

Public Safety



[Source: www.meshdynamics.com]

Intelligent Transportation System



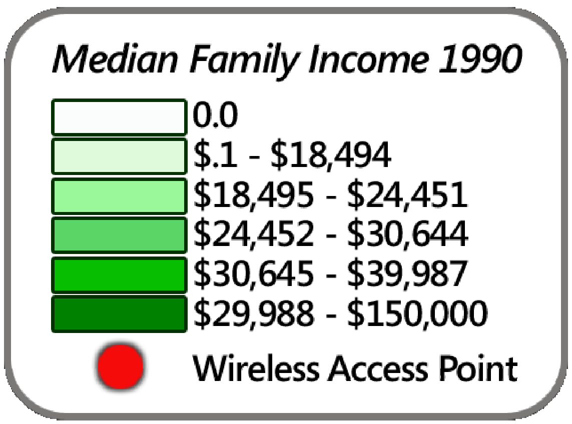
Real Time Information Bus Stops

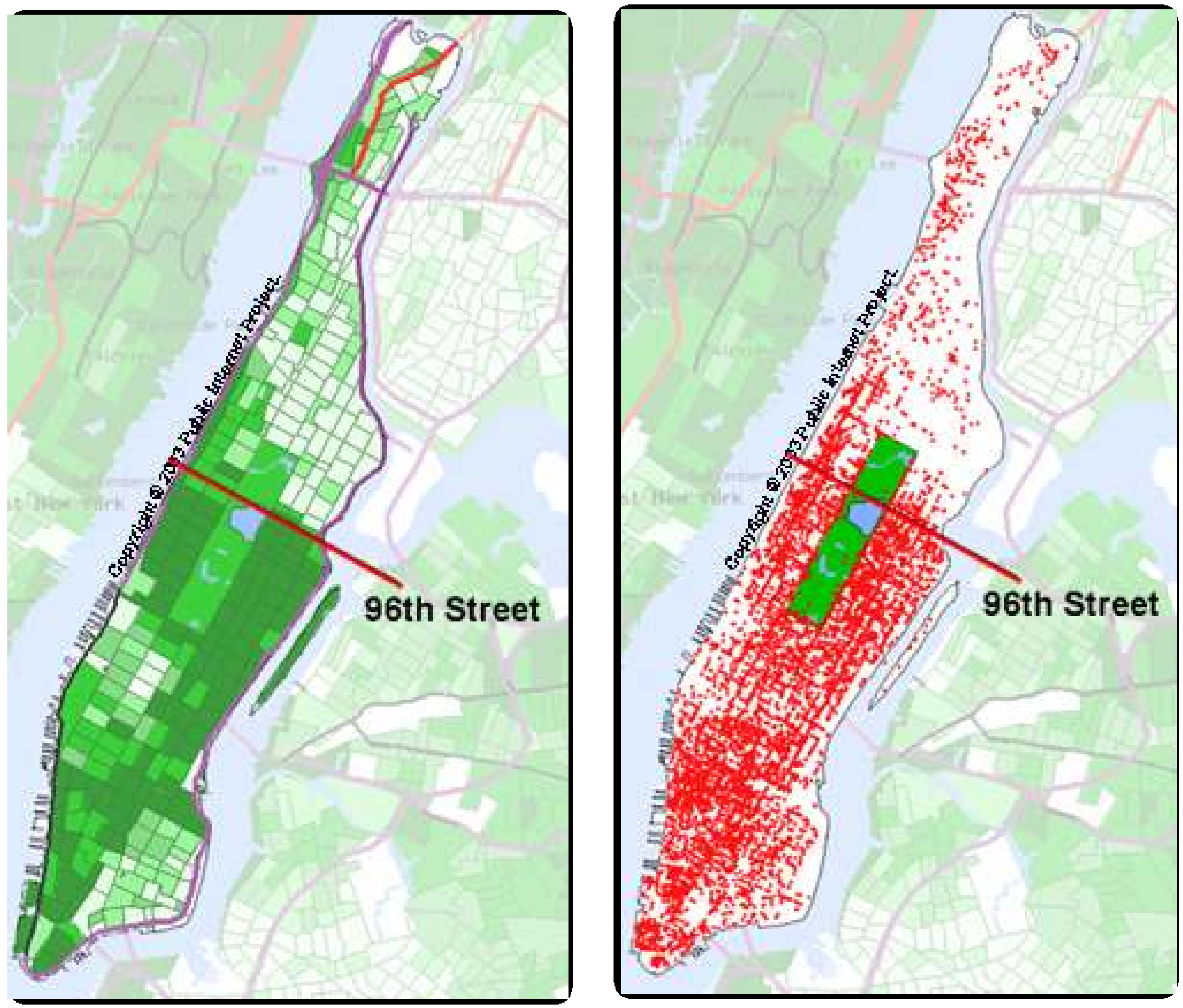
I+ Information Kiosk

[Source: Intelligent Transport Systems City of Portsmouth, IPQC Mesh Networking Forum presentation, 2005]

"Broadband Divide" in Wireless Space

- 13,707 unique nodes within Manhattan (Fall 2002)
- 91% below 96th Street

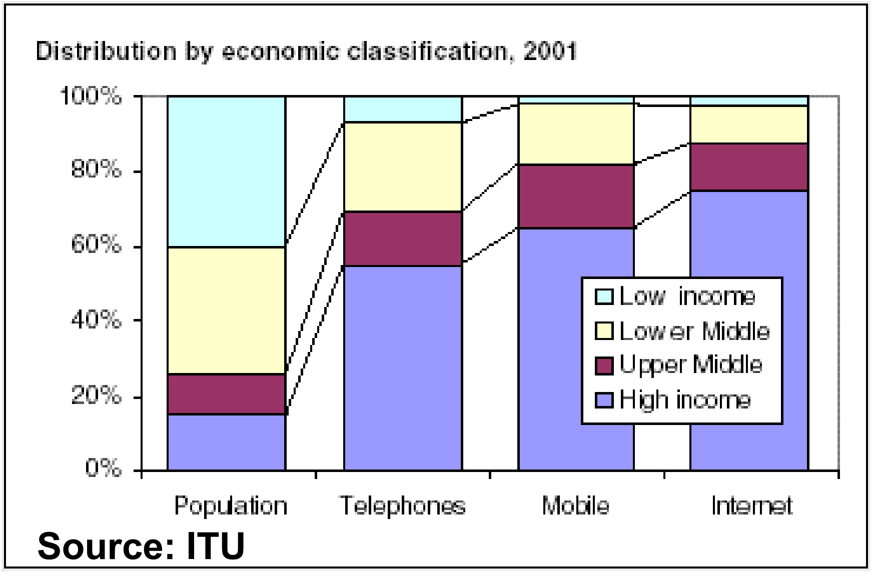


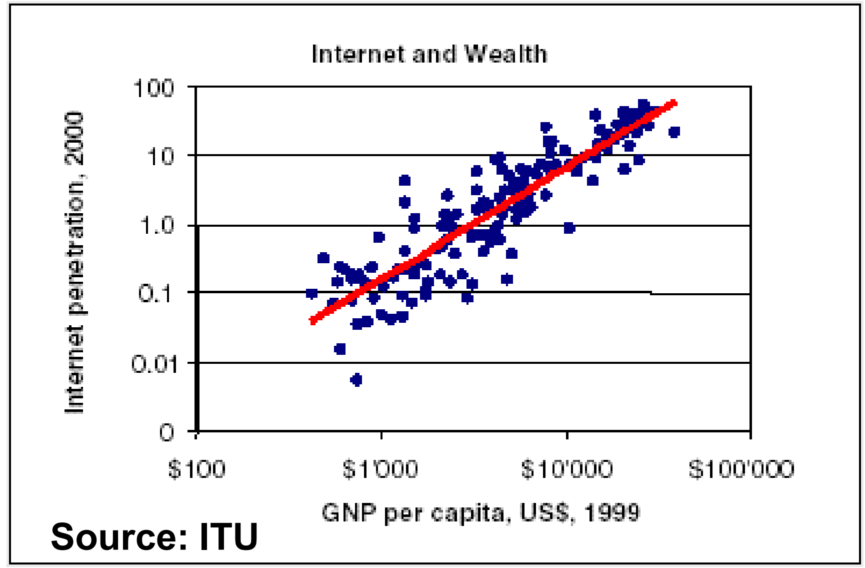


Source: http://publicinternetproject.org

[Acknowledgment: Victor Bahl, Microsoft Research]

Addressing the Digital Divide





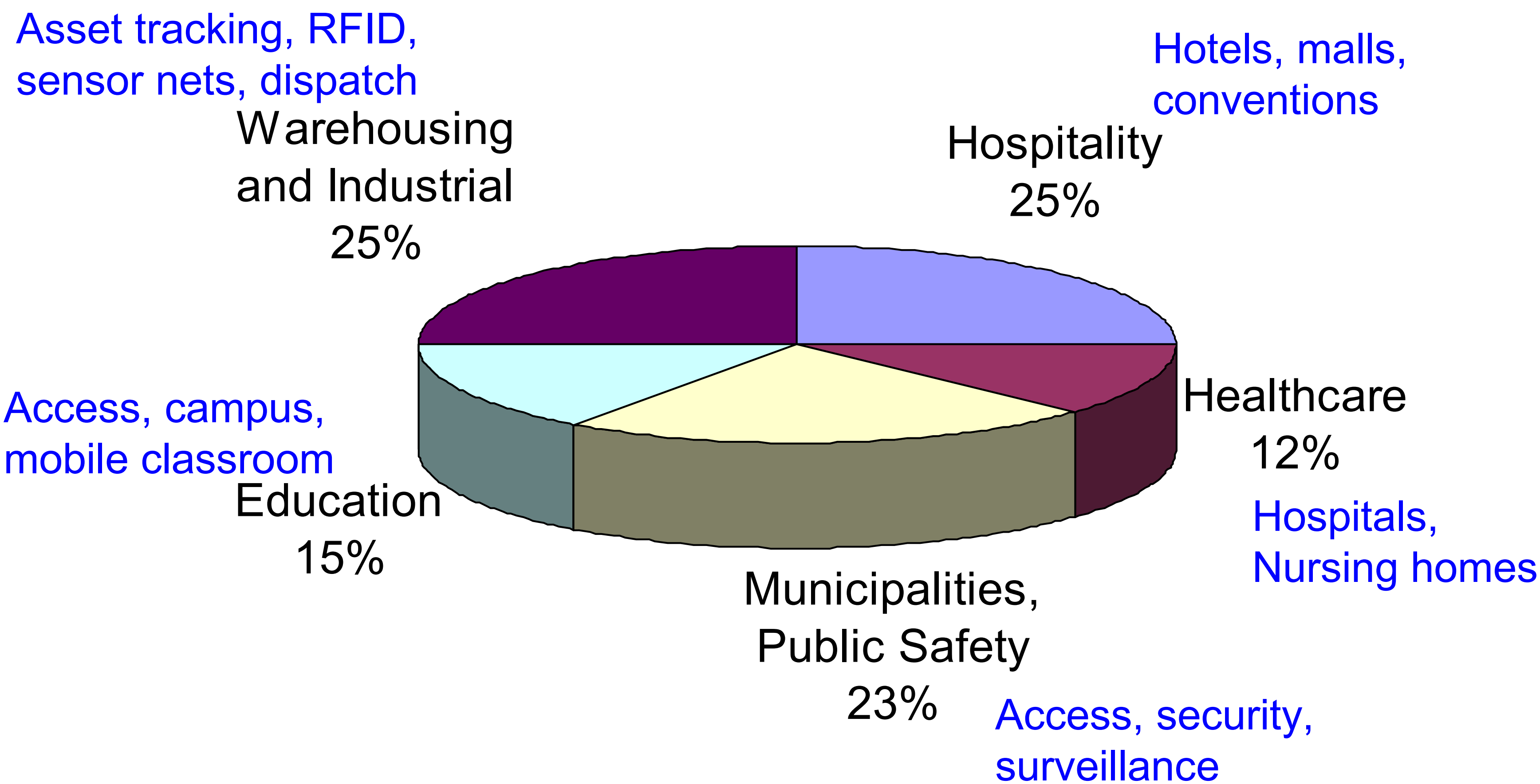
- Internet penetration positively correlated with per capita GNP.
- Need affordable and fast last mile connectivity.
- Tremendous opportunities in developing countries.

Many Service Models

- Private ISP (paid service)
- City/county/municipality efforts
- Grassroots community efforts

- May be shared infrastructure for multiple uses
  - Internet access
  - Government, public safety, law enforcement
  - Education, community peer-to-peer

Market Opportunities



Estimated $1B market by 2009 [source: IDC, ABI]

Several Industry Players

- Firetide
- Intel
- Kiyon
- Locust World
- Mesh Dynamics
- Microsoft
- Motorola /Mesh Networks
- Nokia Rooftop
- Nortel Networks
- Packet Hop
- SkyPilot Networks
- Strix Systems
- Tropos Networks

- Not a comprehensive list.
- Technical details usually proprietary.
- Solutions typically based on standard 802.11, single or multiple radios, standard routing solutions.

Is the Current 802.11 Standard Sufficient?

- Current IEEE 802.11 standard provides a 4-address frame format to exchange packets between APs.
- Inter-AP communication possible
  - WDS (Wireless distribution system).
- However, standard does not specify or define how to configure or use WDS.
  - Multihop forwarding/routing is now a higher layer issue.
- 802.11 MAC itself not suitable for multihop.

IEEE 802.11s ESS Mesh Networking

- Goal: Produce an amendment to the 802.11 standard to create a wireless distribution system
  - Support for unicast and broadcast/multicast.
  - Self-configuring multihop topology
  - Radio aware metrics; possible alternative path selection; supporting protocols based on application requirements.
  - Functionally equivalent to wired ESS.
- Target no of packet forwarding nodes: ~32.

IEEE 802.11s ESS Mesh Networking

- Use 802.11i security or an extension.
- Use 802.11 4-address scheme or an extension.
- Interface with higher layers.

Similar Ideas in History

- **Packet Radio and Mobile Ad Hoc Networks**
  1972: Packet Radio NETwork (PRNET)
  1980s: SURvivable Adaptive Radio Network (SURAN)
  Early 1990s: GLObal MObile Information System (& NTDR)
  Research agenda mostly set by DoD. Applications mostly military.
  Mid 1990s: IETF MANET. Applications military/tactical, emergency response, disaster recovery, explorations, etc. Goal: standardize a set of IP-based routing protocols.
- Scenarios too specific. Little commercial impact in spite of 30 years of research.

History (contd.)

- However, great strides in several fronts in ad hoc networking research
  - Understanding routing in dynamic networks.
  - Understanding MAC protocols for wireless multihop networks.

How Much We can Borrow from History?

- A lot .. But issues are different now.
  - In MANET design for mobility.
  - In mesh network design for capacity.
- Advantage: can afford more power and bigger size.

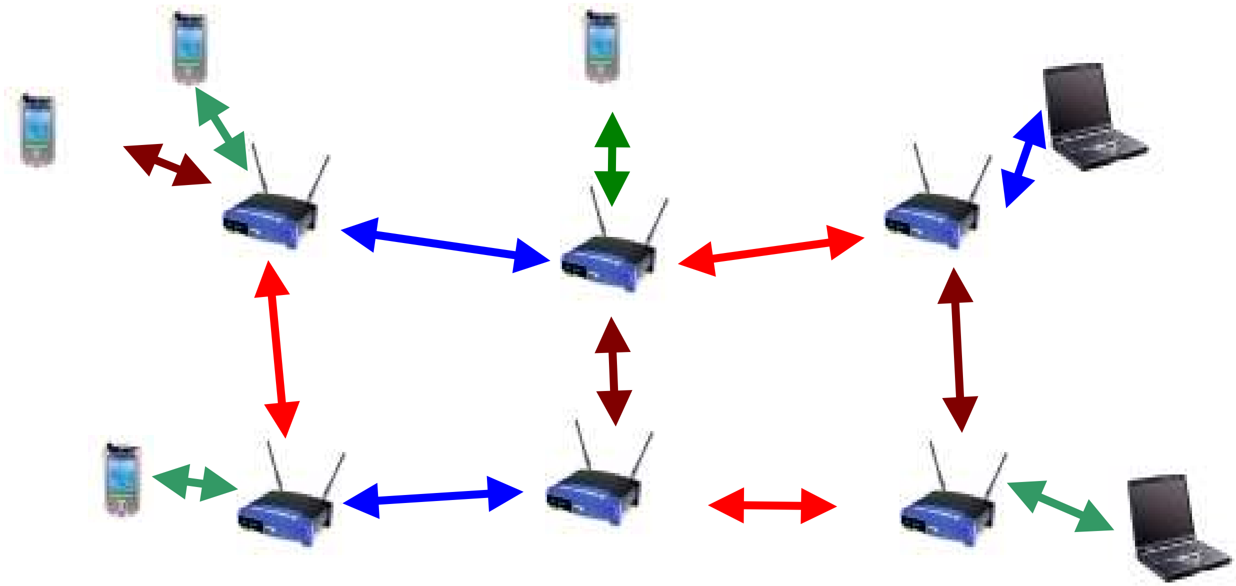
Research Challenges

- Wireless is not like wired networks.
  - Wireless links interfere.
  - Intra-flow and inter-flow interference.
- Theoretical models show significant capacity degradation because of the wireless interference.

This Talk

- How to improve capacity using multiple channels?
- How to model interference in real networks?
- Focus on deployable practical approaches.

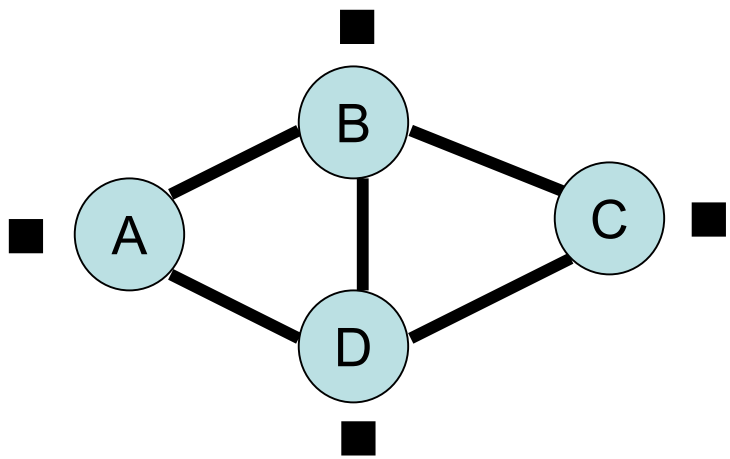
Single Radio Approach



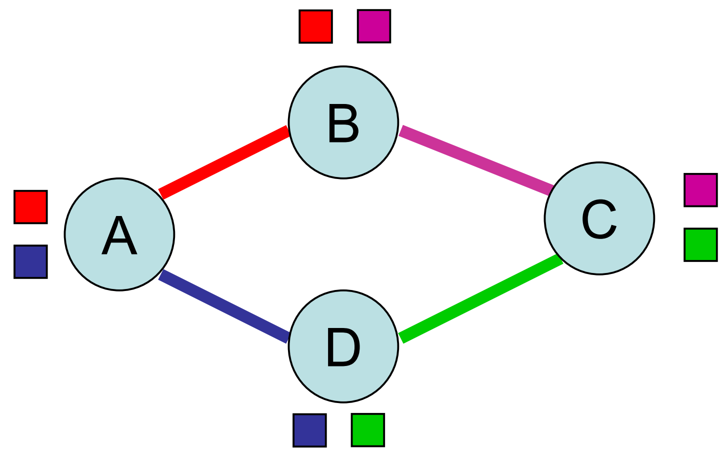
- Single radio interface poses two challenges:
  - Channel switching latency (in order of ms in commodity 802.11 cards).
  - Coordination between sender-receiver.

- Responses:
  - Ignore latency issue. Or, use multiple transmissions per switch to amortize cost.
  - Use separate control channel, or tight timing synch and rendezvous, or slot assignments.

Channel Assignment Problem



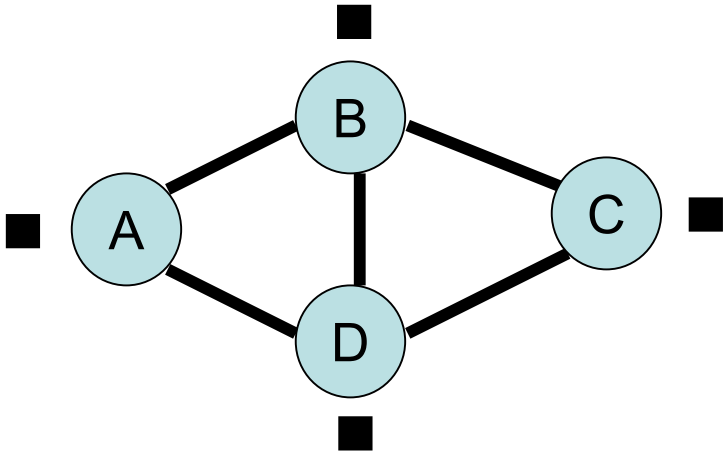
1 channel
1 interface



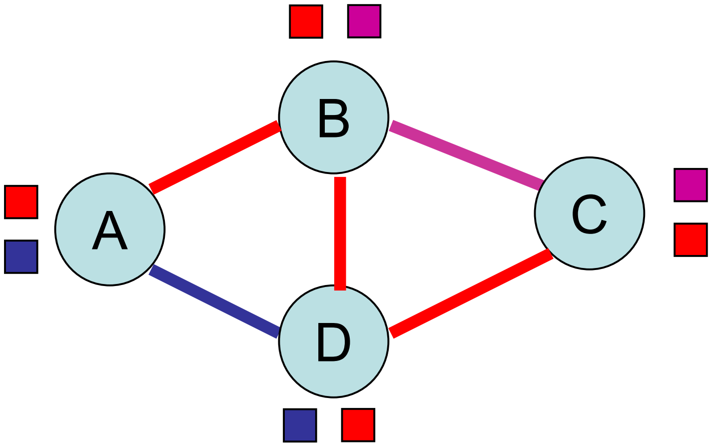
4 channels,
2 interfaces

- Channel assignment can control topology.
- Two nodes can communicate when they have at least one interface in common channel.

Channel Assignment Problem



1 channel
1 interface



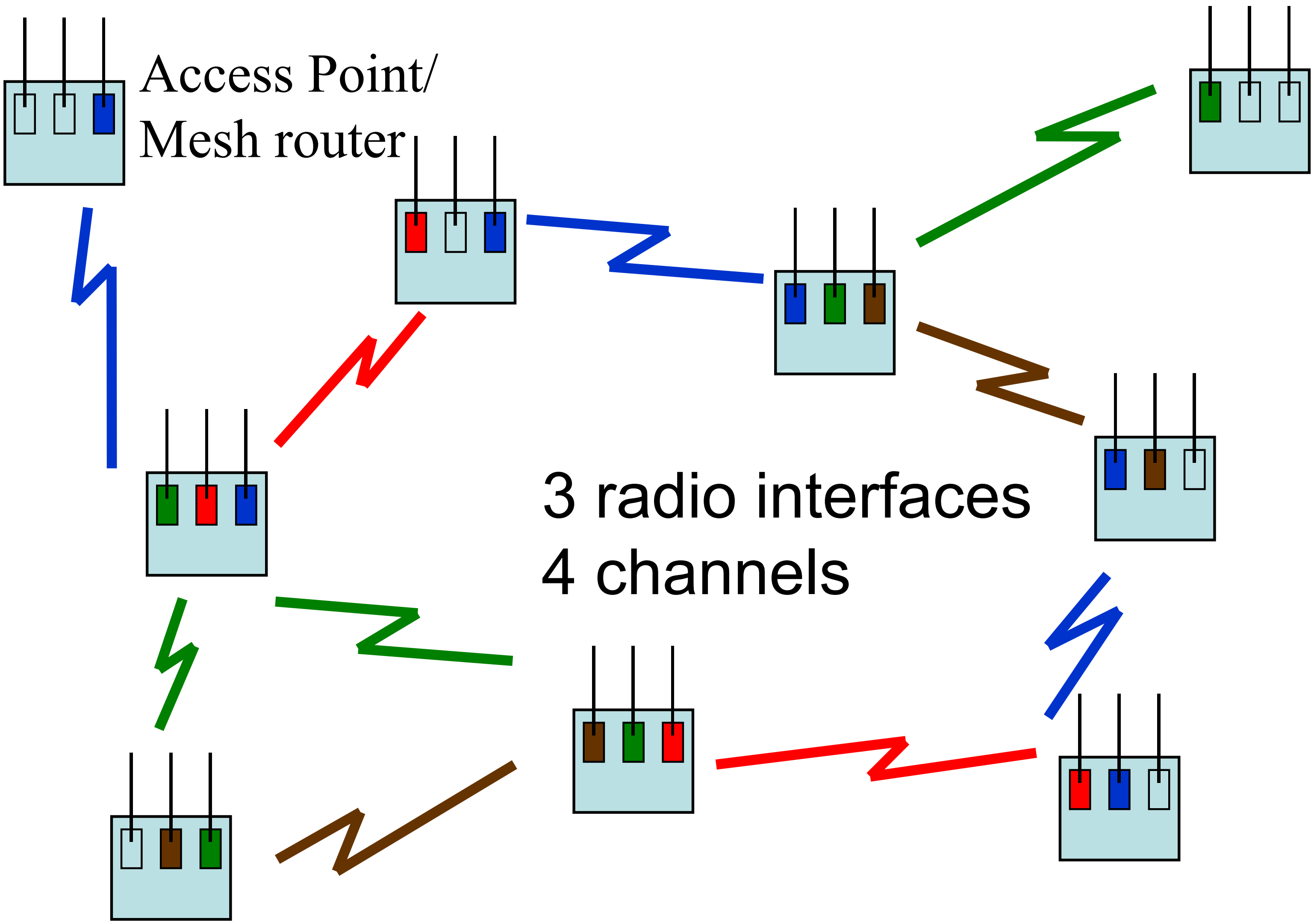
4 channels,
2 interfaces

- Channel assignment can control topology.
- Two nodes can communicate when they have at least one interface in common channel.

iMesh: Stony Brook's Mesh Router

Small embedded platform running Linux with 2-3 WiFi interfaces. Runs routing and mobility management software.

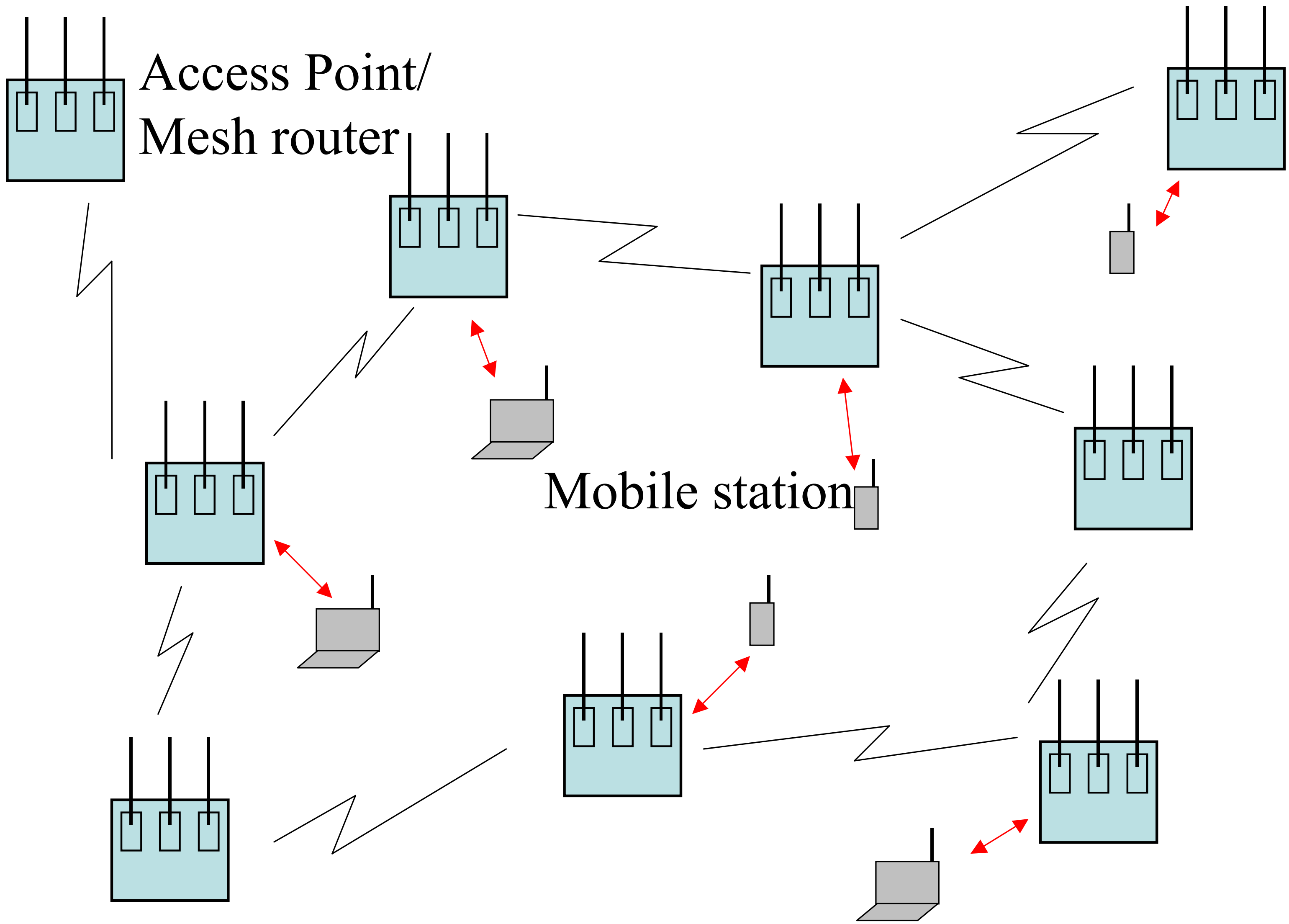
iMesh: A Multiradio, Multichannel Mesh



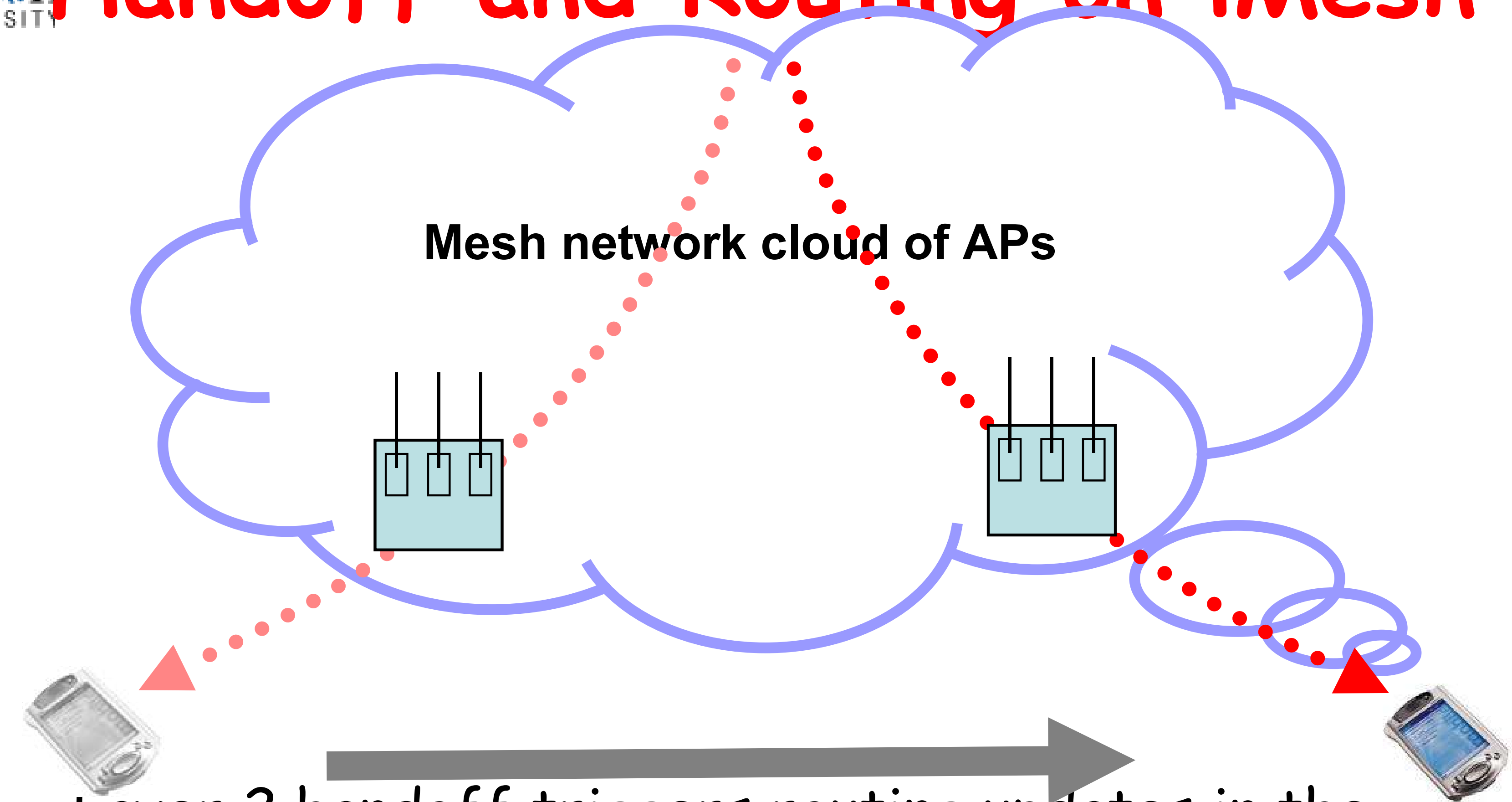
Topology Preserving Channel Assignment

- Preserve all links.
- Modeled as constrained *k*-coloring problem. NP-Complete Problem.
- Developed efficient heuristic algorithms. Algorithm can run on a central network controller.
- With 4 radios per router, 75%-90% of interferences removed for a 12 channel scenario. Means 75%x12 – 90%x12 times capacity improvement over single channel.

iMesh: Experimental Testbed

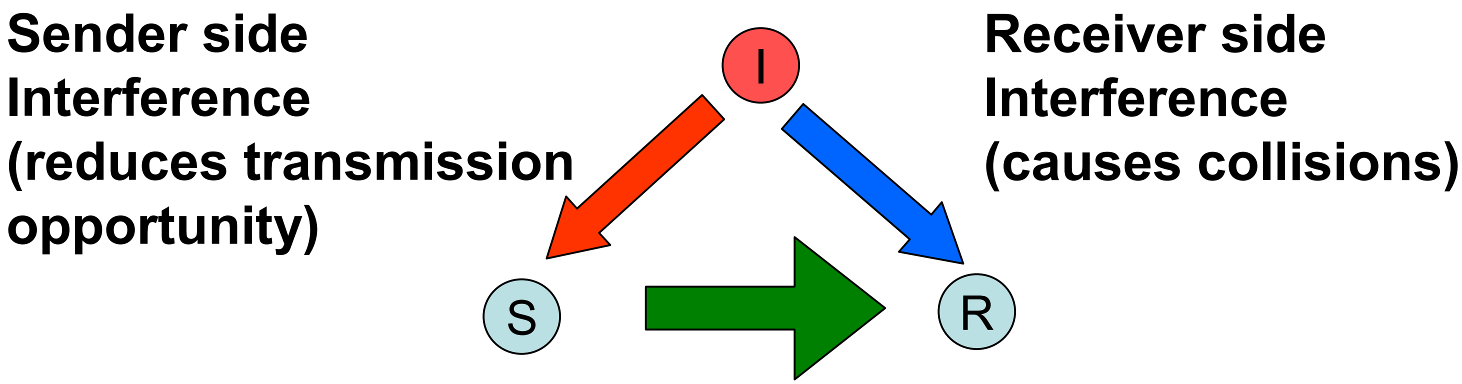


Handoff and Routing on iMesh



- Layer 2 handoff triggers routing updates in the mesh backbone (Layer 3 handoff).
- 10-20ms additional latency in Layer 3 for upto 5 hop route changes.
- Fine for interactive voice and video.

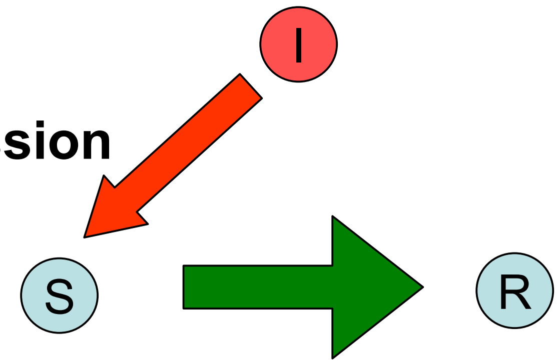
Capacity in Presence of Interference



- Assume, sender S and Interferer I always backlogged.
- Capacity of SR link = normalized transmission rate* delivery ratio * (1- Prob. of collision).

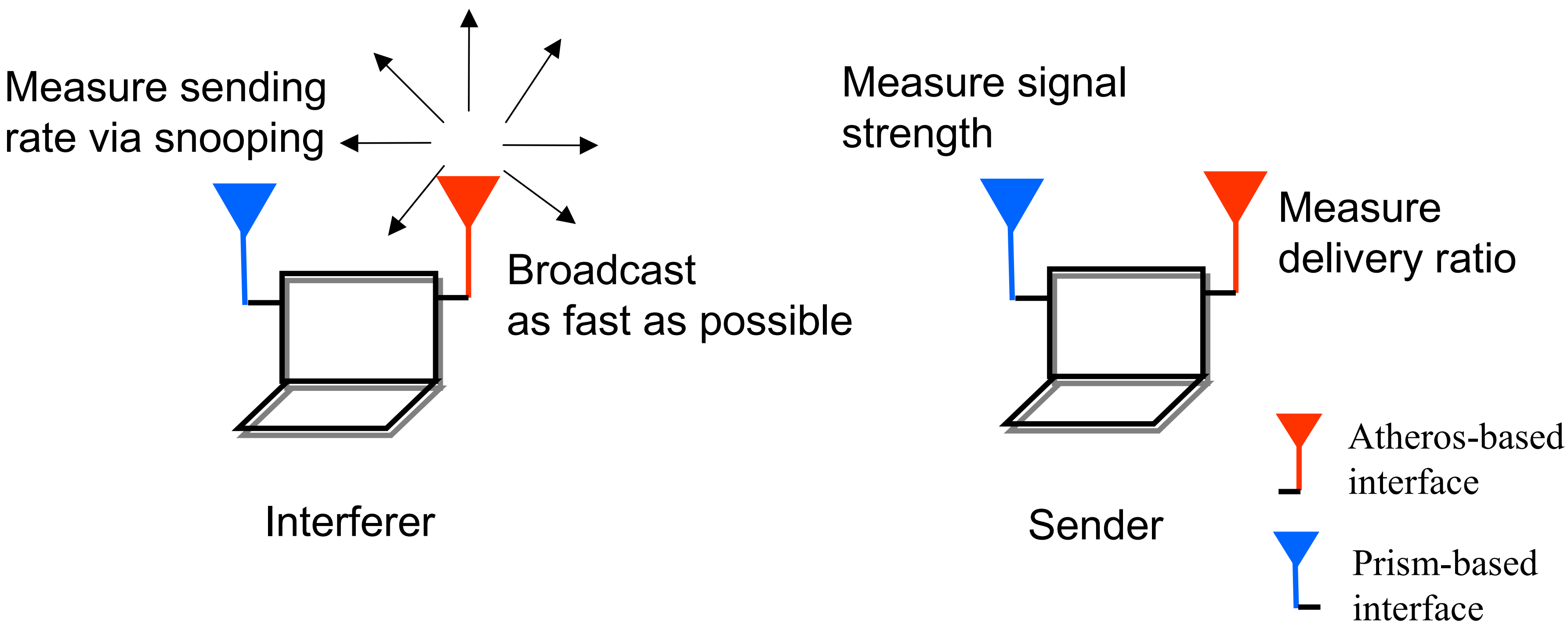
Modeling Sender Side Interference

Sender side Interference (reduces transmission opportunity)



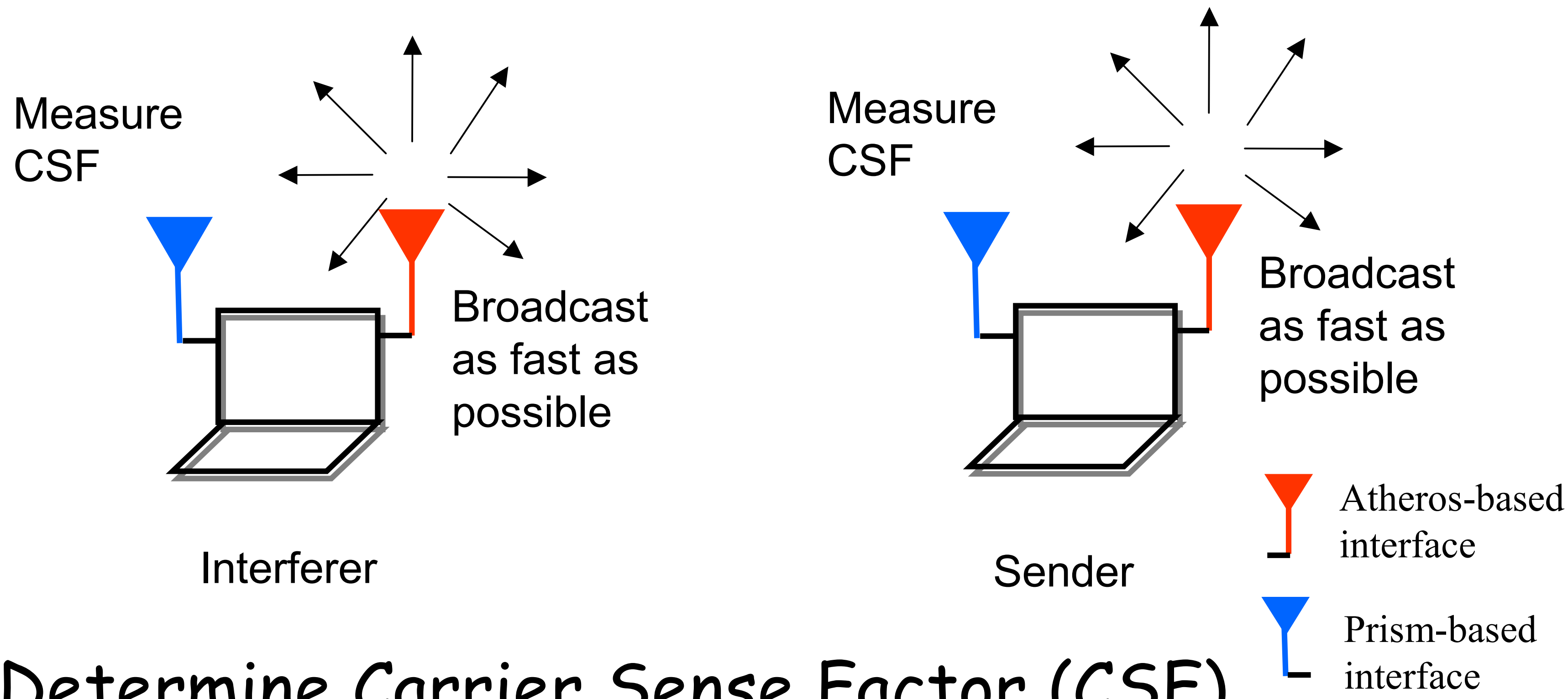
- Carrier Sense Factor, CSF(S,I) = Normalized transmission rate of S in presence of I.
- Hypothesis: The quality of I to S link is a good predictor of CSF(S,I).
- Challenge: How to measure link quality?

Experimental Setup



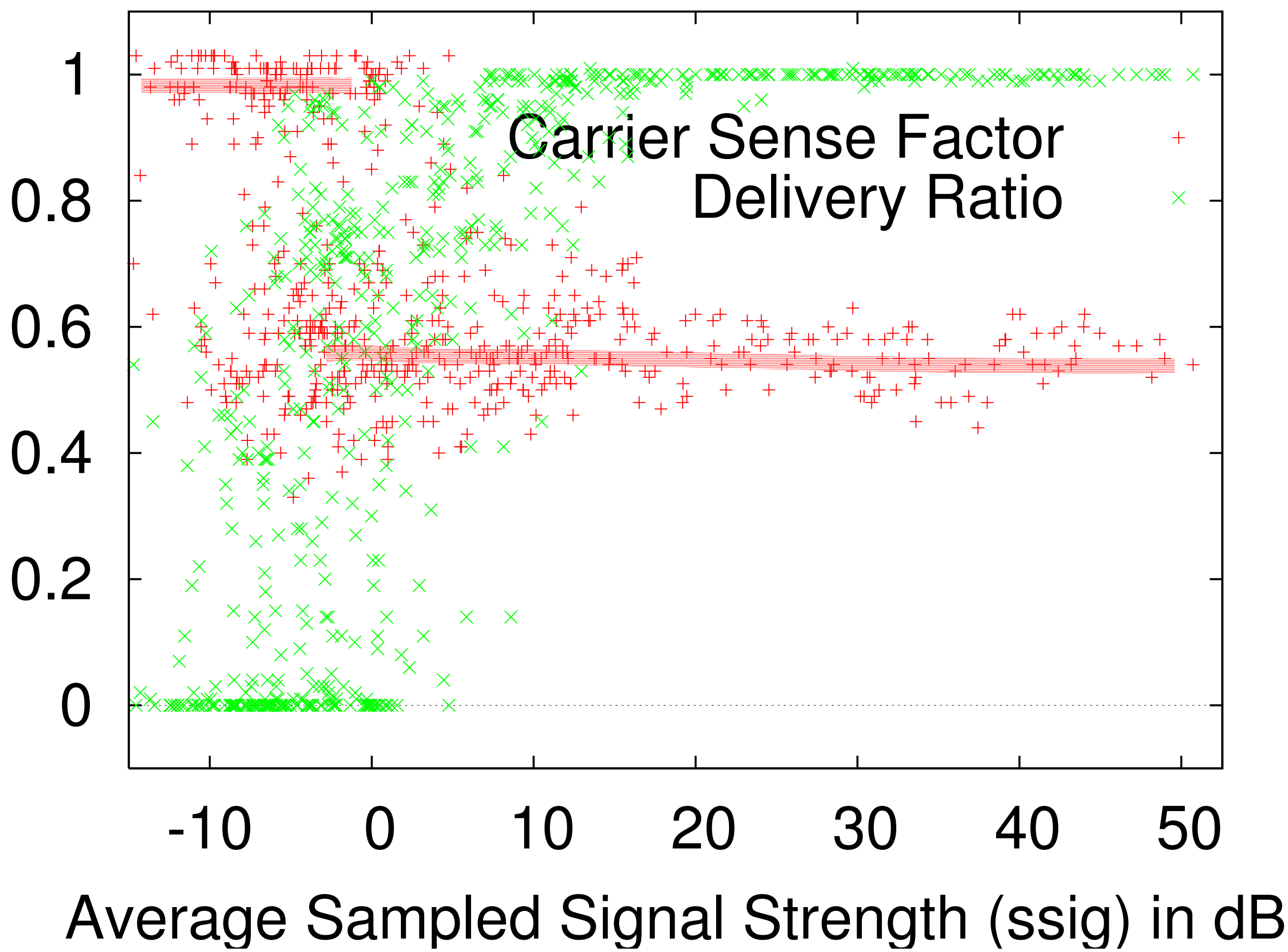
- Determine quality of the link from interferer to sender.

Experimental Setup

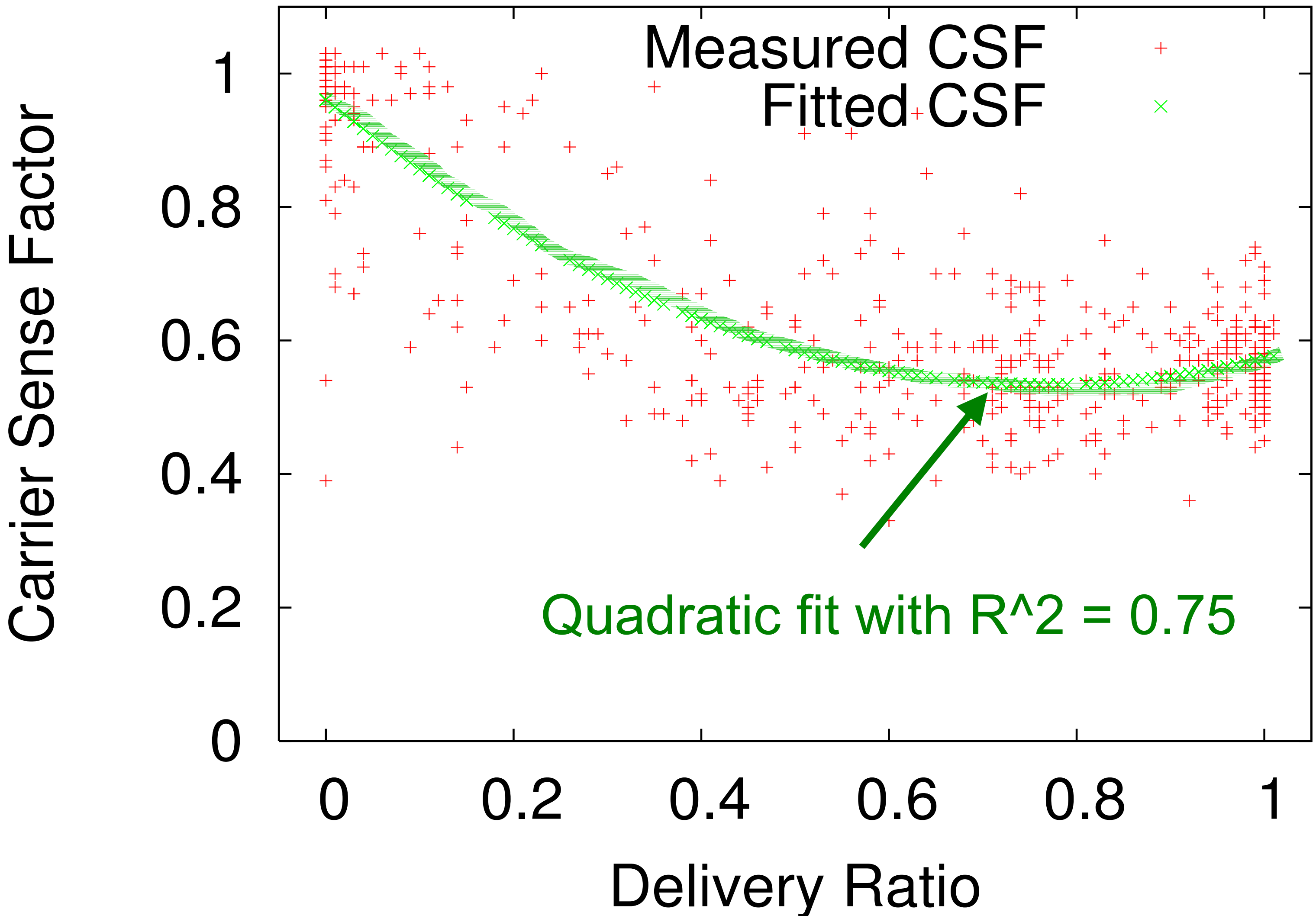


- Determine Carrier Sense Factor (CSF).
- Repeat experiments by changing positions.
- Over 600 positions measured in indoor environment (robot assisted).

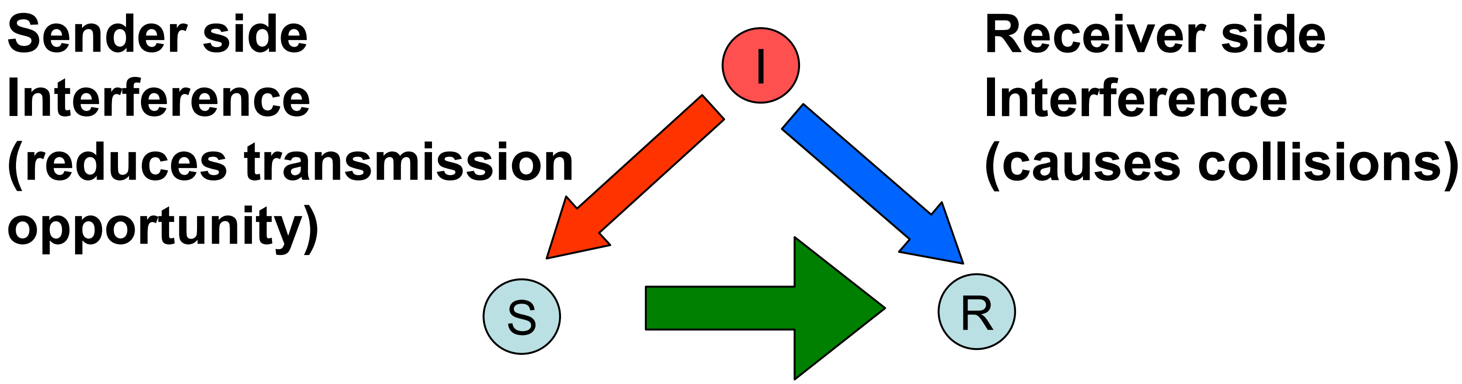
Relationship between CSF and DR with Signal Strength



Predict CSF with Delivery Ratio



Recall



- Assume, sender S and Interferer I always backlogged.
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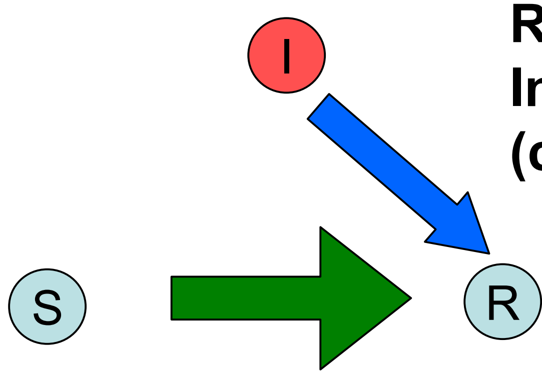
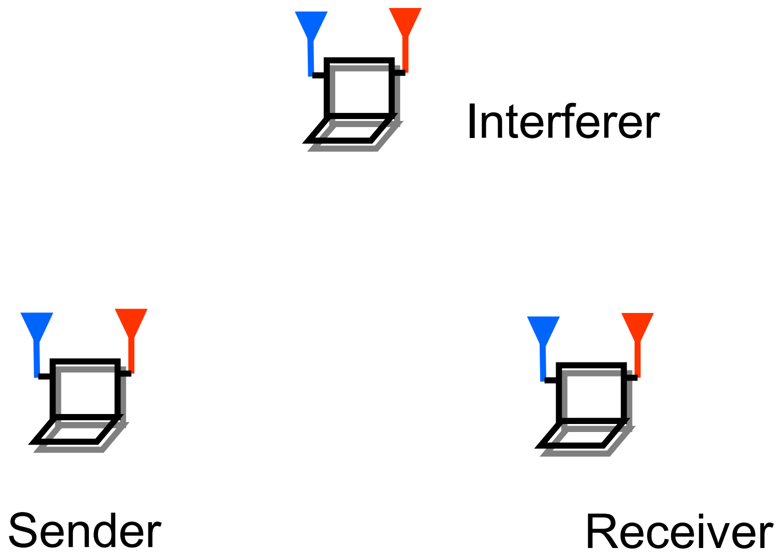
Modeling Receiver-side Interference



Receiver side Interference (causes collisions)

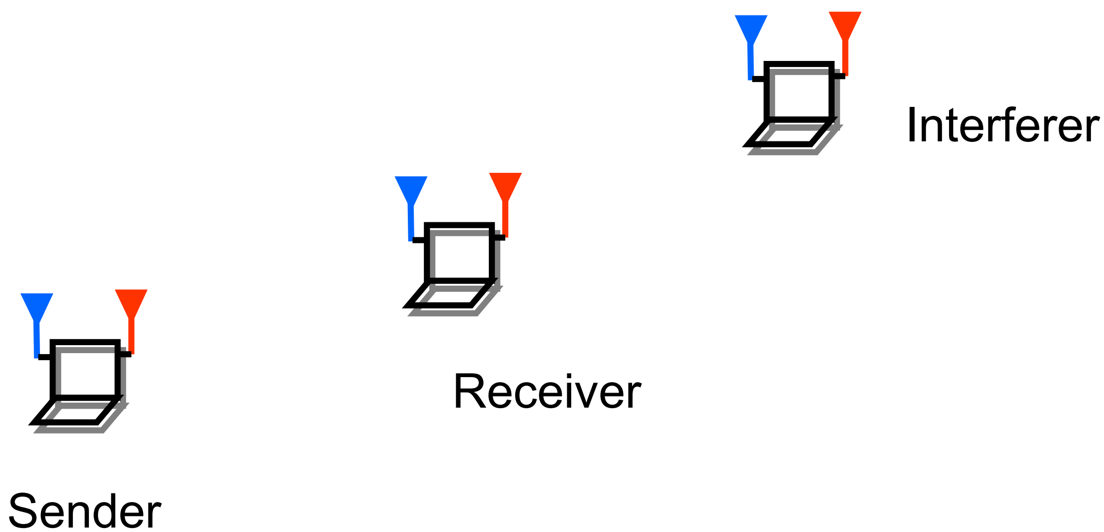
- No collision if signal strength from S - signal strength I > threshold (dB).
- Else, Prob. of collision = delivery ratio * (CSF(I,S)+CSF(S,I)-1)/CSF(S,I)

Putting Both Sides Together



- 600 experiments with different link qualities between sender, receiver, interferer.
- Both sender and interferer transmit at the max possible rate.

Putting Both Sides Together



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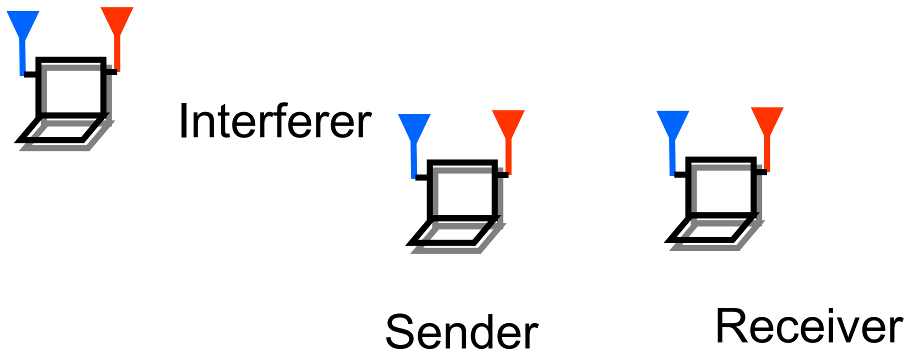
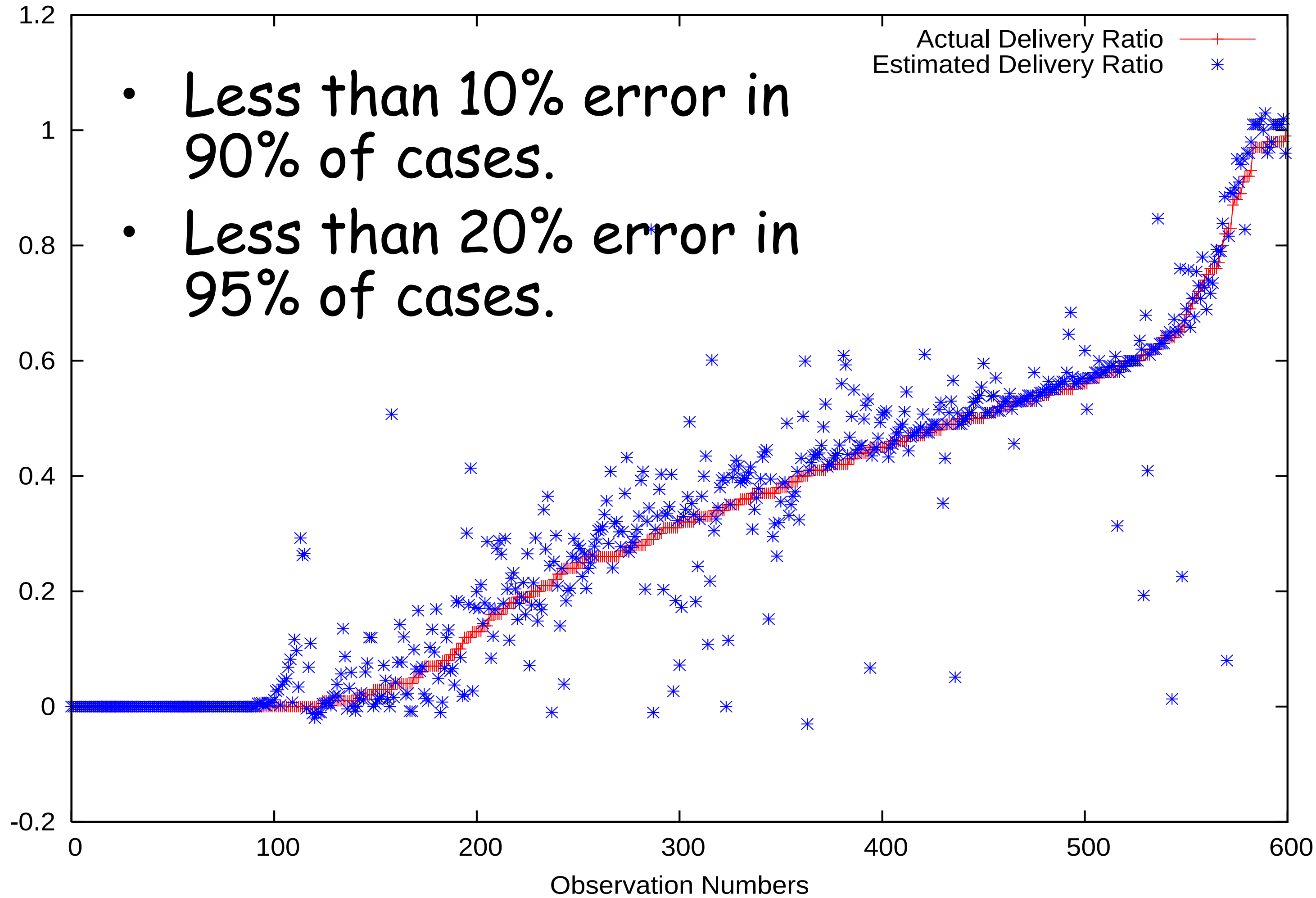


- 600 experiments with different link qualities between sender, receiver, interferer.
- Both sender and interferer are always backlogged.

Putting Both Sides Together

- Less than 10% error in 90% of cases.
- Less than 20% error in 95% of cases.



What is the value?

- We can determine the capacity of any link in presence of interference from any node
  - Only need to know delivery ratio and signal strengths between every node pair (without interference).
  - Can be measured using the radio interfaces themselves.
- Capacity model can be used for capacity planning, channel assignment, VoIP admission control.
  - Also can be used in simulations.

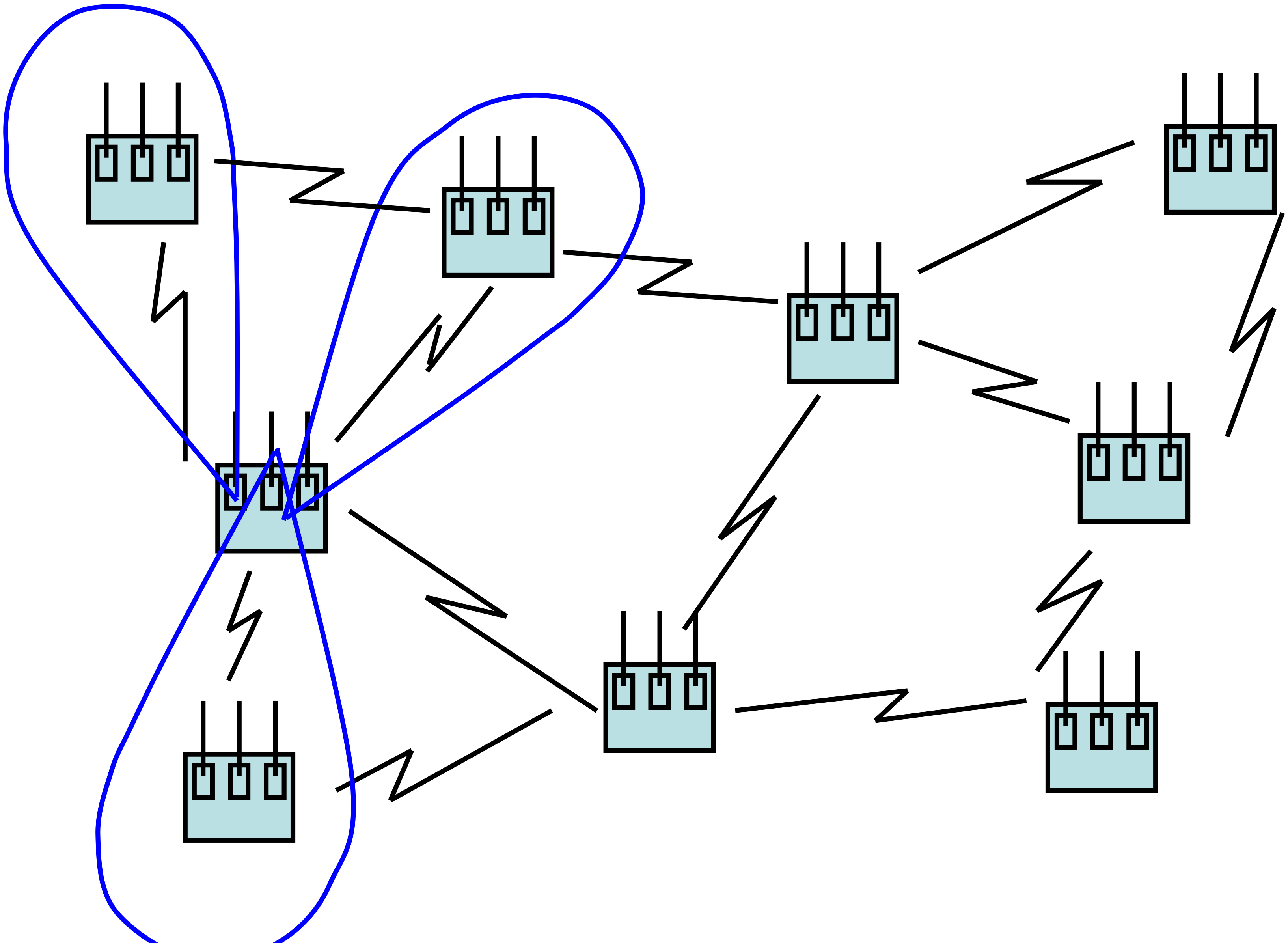
Summary

- WiFi Mesh is here.
    - But interference limits capacity.
- Multi-radio channel assignment
    - Single radio solution not compatible with commodity hardware.
- Measurement-based interference modeling.
    - Can be used to model and predict network capacity.

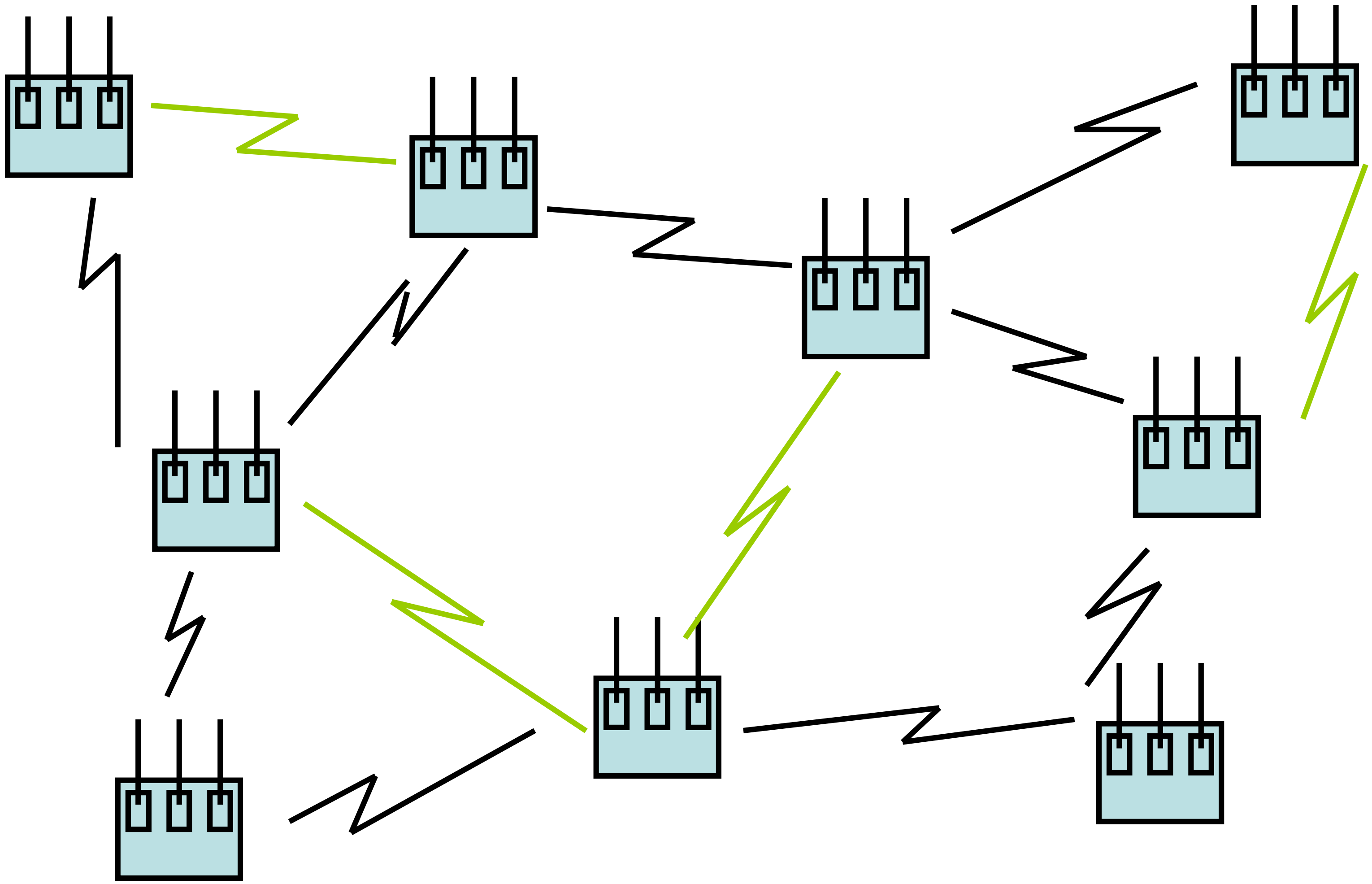
Using Directional Antennas

- Directional antenna reduces interference.
- However, effective use requires smart antenna as well as new MAC protocols.
- iMesh solution: inexpensive antennas and legacy 802.11 MAC.

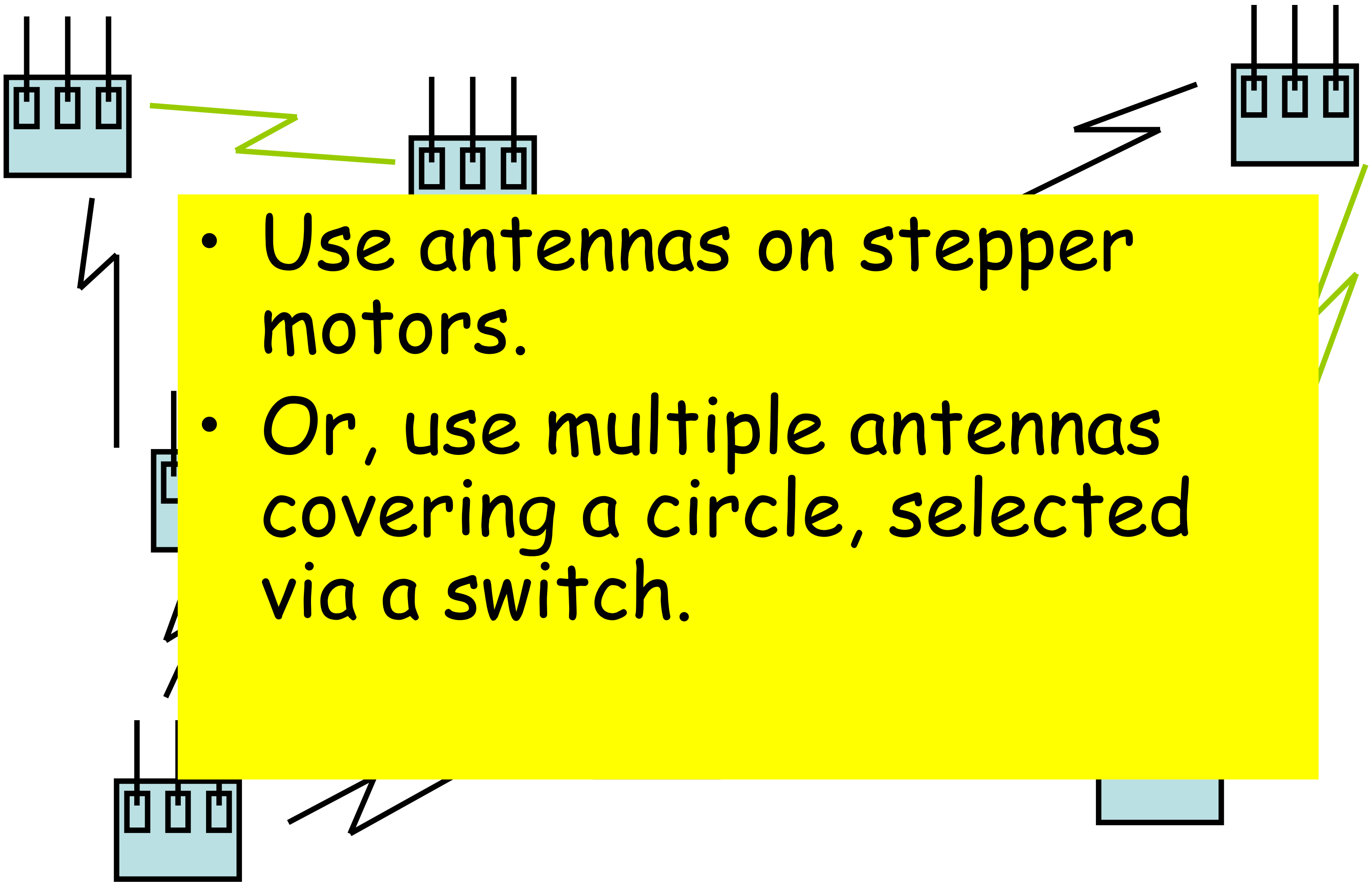
Using Directional Antenna



Topology Control with Directional Antennas



Topology Control with Directional Antennas



- Use antennas on stepper motors.
- Or, use multiple antennas covering a circle, selected via a switch.

Topology Control with Directional Antennas

- How to orient antennas so that enough connectivity is retained, but overall interference is reduced?
- New algorithms achieve major improvement in end-to-end throughput.
- Simulation results for a 100 node network: 3-4 times improvement in throughputs with single channel, 3 antennas per node (30^0 beamwidth).

Final Thoughts

- "Performance transparency" is important.
- Possible even with COTS hardware.
- Key techniques: fast handoff, multi-radio/multichannel, directional antennas.
- Thanks to our sponsors: NSF, CEWIT (NY State), Computer Associates, NEC Labs.