



# *Cognitive Radio Networks & The Future Internet*

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DIMACS Tutorial on Next Generation Networks

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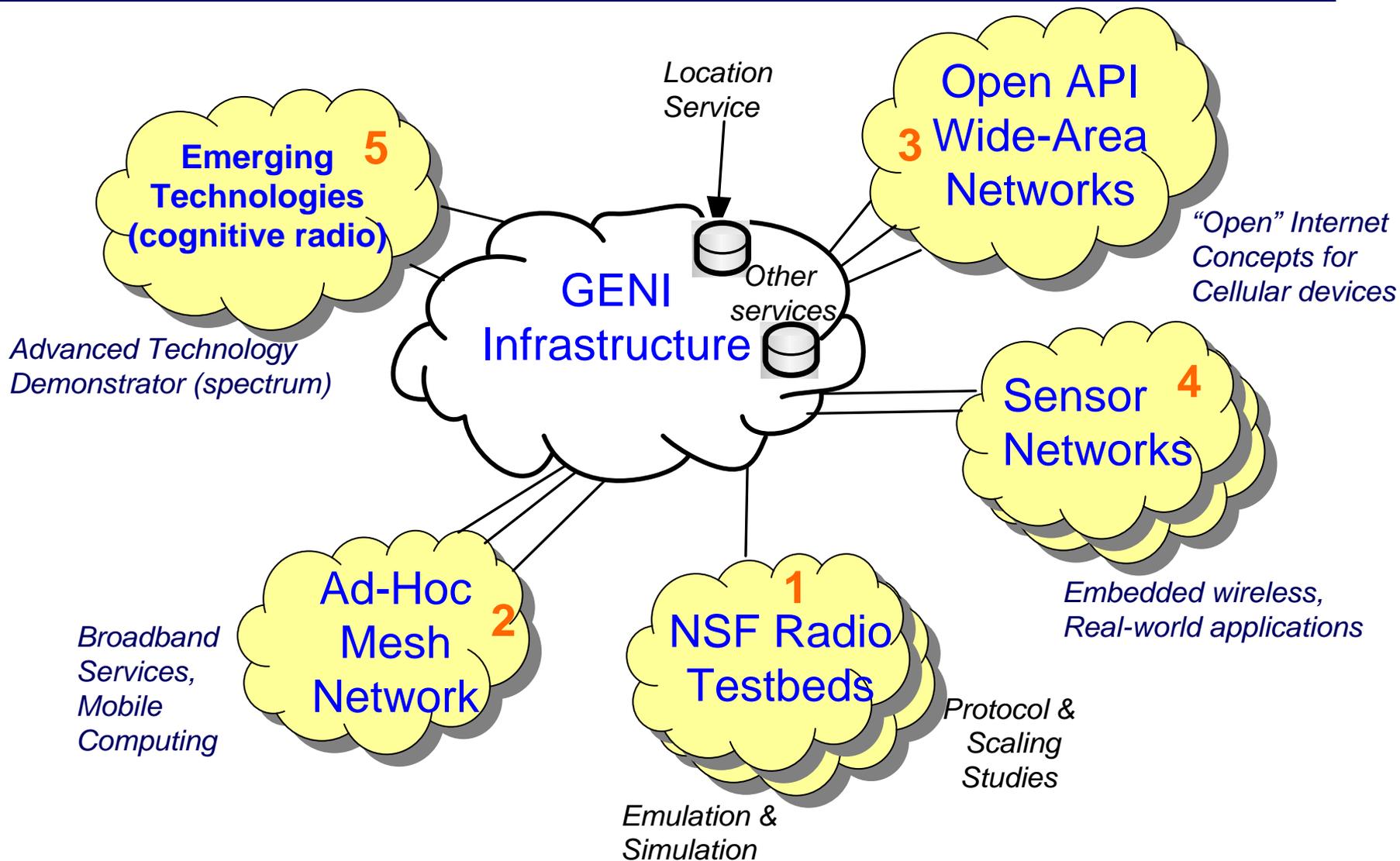
# Wireless and the Future Internet

- “Wireless” is overtaking “Wired” as the primary mode of connectivity to the internet
  - 500 M Internet-connected servers/PCs vs. 2 B cell phones (over 400M internet capable and growing ..... )
  - Several new types of wireless devices in the market - evolving and growing
  - Sensor deployments just beginning - ~10 B sensor devices by 2020
- Wireless network usage scenarios that will impact future internet design
  - Mobile data applications
  - Multihop Mesh networks
  - Sensor and vehicular networks

# Wireless/Mobile/Sensor Scenarios and the Future Internet

- Some architectural and protocol implications for the future Internet...
  - Integrated support for dynamic end-user mobility
  - Wireless/mobile devices as routers (mesh networks, etc.)
  - Network topology changes more rapidly than in today's wired Internet
  - Significant increase in network scale (10B sensors in 2020!)
  - New ad hoc network service concepts: sensors, P2P, P2M, M2M,...
  - Addressing architecture issues - name vs. routable address
  - Integrating geographic location into routing/addressing
  - Integrating cross-layer and cognitive radio protocol stacks
  - Data/content driven networking for sensors and mobile data
  - Pervasive network functionality vs. broadband streaming
  - Power efficiency considerations and computing constraints for sensors
  - Many new security considerations for wireless/mobile
  - Economic incentives, e.g. for forwarding and network formation

# NSF GENI Implementation Wireless Sub-Networks Overview



# Motivation for Dynamic Spectrum and Cognitive Radio Techniques:

- **Static allocation of spectrum is inefficient**
  - Slow, expensive process that cannot keep up with technology
- **Spectrum allocation rules that encourage innovation & efficiency**
  - Free markets for spectrum, more unlicensed bands, new services, etc.
- **Anecdotal evidence of WLAN spectrum congestion**
  - Unlicensed systems need to scale and manage user "QoS"
- **Density of wireless devices will continue to increase**
  - ~10x with home gadgets, ~100x with sensors/pervasive computing
- **Interoperability between proliferating radio standards**
  - Programmable radios that can form cooperating networks across multiple PHY's

# Towards Cognitive Radio Networks- Recent Research Developments

Research themes that have emerged from mobile ad hoc and/or sensor networks research:

- **Hierarchical Network Architecture wins**
  - Capacity scaling, energy efficiency, increases lifetimes, facilitates discovery
- **Cooperation wins**
  - Achievable rates via information theoretic relay and broadcast channels
- **"Global" awareness and coordination wins**
  - Space, time and frequency awareness and coordination beyond local measurements
- **Efficient operation requires radios that can:**
  - Cooperate
  - Collaborate
  - Discover
  - Self-Organize into hierarchical networks

# Cognitive Radio Research

## A Multidimensional Activity

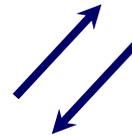
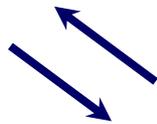
### ■ Spectrum Policy

- Economics
- Regulation
- Legal
- Business



### ■ Theory and Algorithms

- Fundamental Limits
- Information & Coding Theory
- Cooperative Communications
- Game Theory & Microeconomics



### ■ Hardware/Software Platforms & Prototyping

- Programmable agile radios
- GNU platforms
- Cognitive Radio Network Testbed

# The Spectrum Debate

## Triumph of Technology vs. Triumph of Economics

### ■ Open Access (Commons)

- [Noam, Benkler, Shepard, Reed ...]
  - Triumph of Technology
  - Agile wideband radios will dynamically share a commons
  - Success of 802.11 vs 3G

### ■ Spectrum Property Rights

- [Coase, Hazlett, Faulhaber+Farber]
  - Triumph of Economics
  - Owners can buy/sell/trade spectrum
  - Flexible use, flexible technology, flexible divisibility, transferability
  - A spectrum market will (by the force of economics) yield an efficient solution

### ■ What everyone agreed on (a few years ago):

- Spectrum use is inefficient
- FCC licensing has yielded false scarcity

# The Spectrum Debate and Cognitive Radio

- What everyone agrees on now:
  - Spectrum use is inefficient
  - FCC licensing has yielded false scarcity
- Possible middle ground?
  - Dynamic spectrum access
  - Short-term property rights
  - Spectrum use driven by both technology and market forces
- Cognitive Radios with ability to incorporate market forces?
  - Microeconomics based approaches to spectrum sharing
  - Pricing and negotiation based strategies
    - (e.g. Ileri & Mandayam, *To appear in IEEE Communications Magazine 2007*)

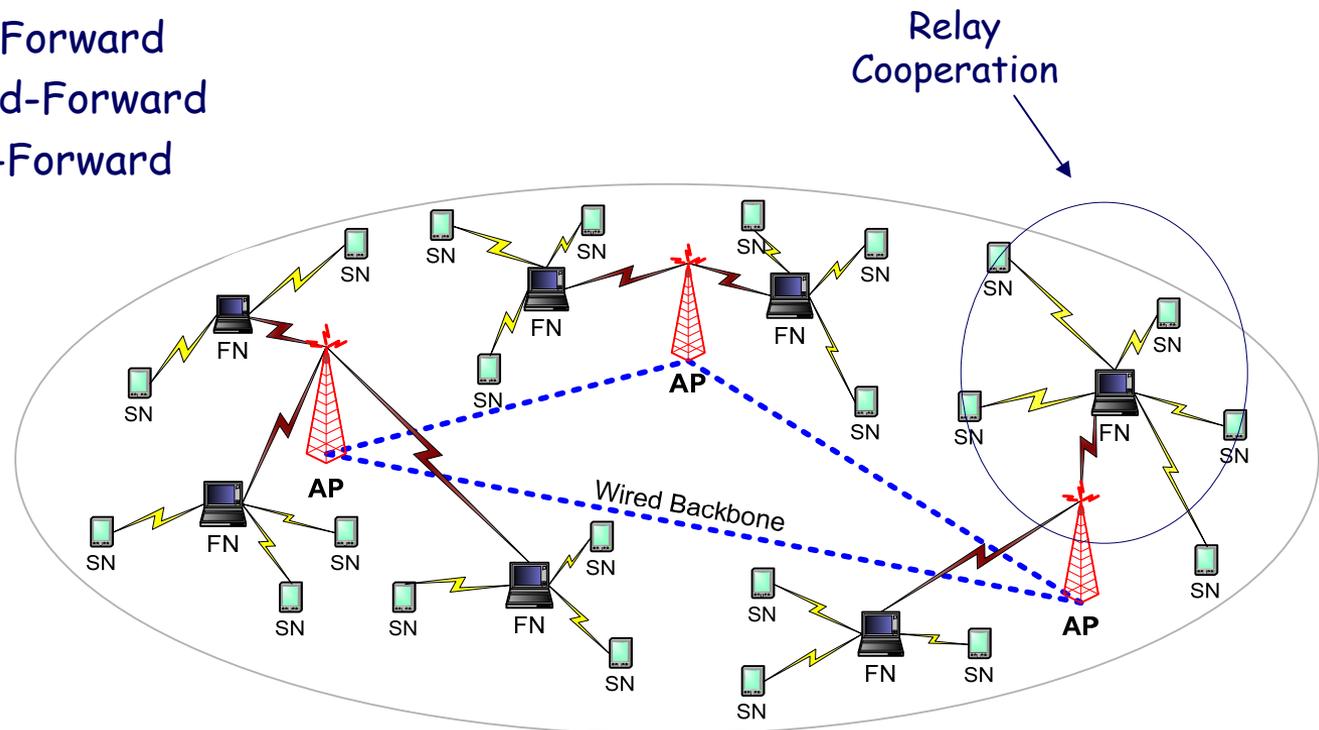
# Cognitive Radio - Theory & Algorithms

Fundamental research and algorithms - based on foundations of:

- Information and Coding Theory
  - Relay cooperation, User Cooperation, Coding techniques for cooperation, Collaborative MIMO techniques
- Signal Processing
  - Collaborative signal processing, Signal design for spectrum sharing, Interference avoidance, Distributed sensing algorithms
- Game Theory
  - Microeconomics and pricing based schemes for spectrum sharing, negotiation and coexistence, Incentive mechanisms for cooperation
- MAC and Networking Algorithms
  - Discovery protocols, Etiquette protocols, Self-organization protocols, Multihop routing

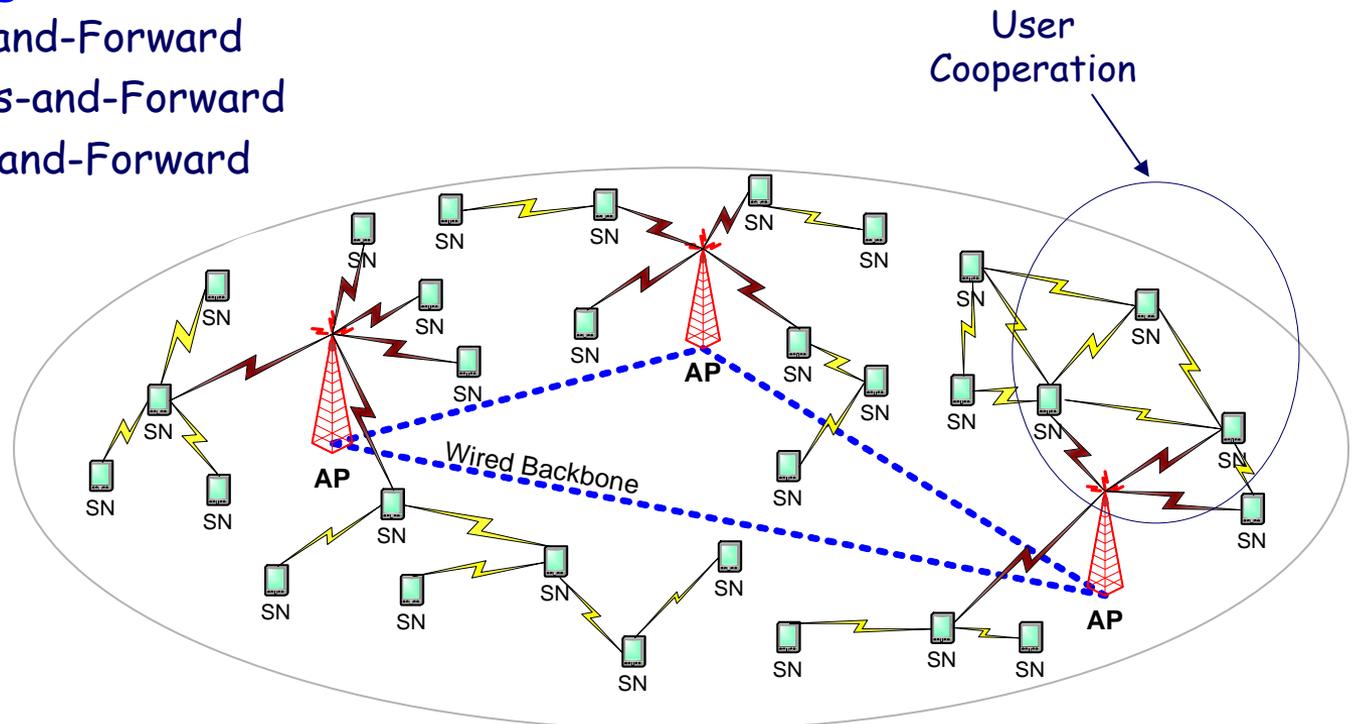
# Information Theoretic Approaches

- Various types of relay cooperation and user cooperation models
  - Cooperation - nodes share power and bandwidth to mutually enhance their transmissions
  - Can achieve spatial diversity - similar to multiple antennas
- Fundamental limits are known in limited cases
- Primary focus on achievable rates, outage and various cooperative coding schemes, e.g.
  - Decode-and-Forward
  - Compress-and-Forward
  - Amplify-and-Forward



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# Game Theory Approaches

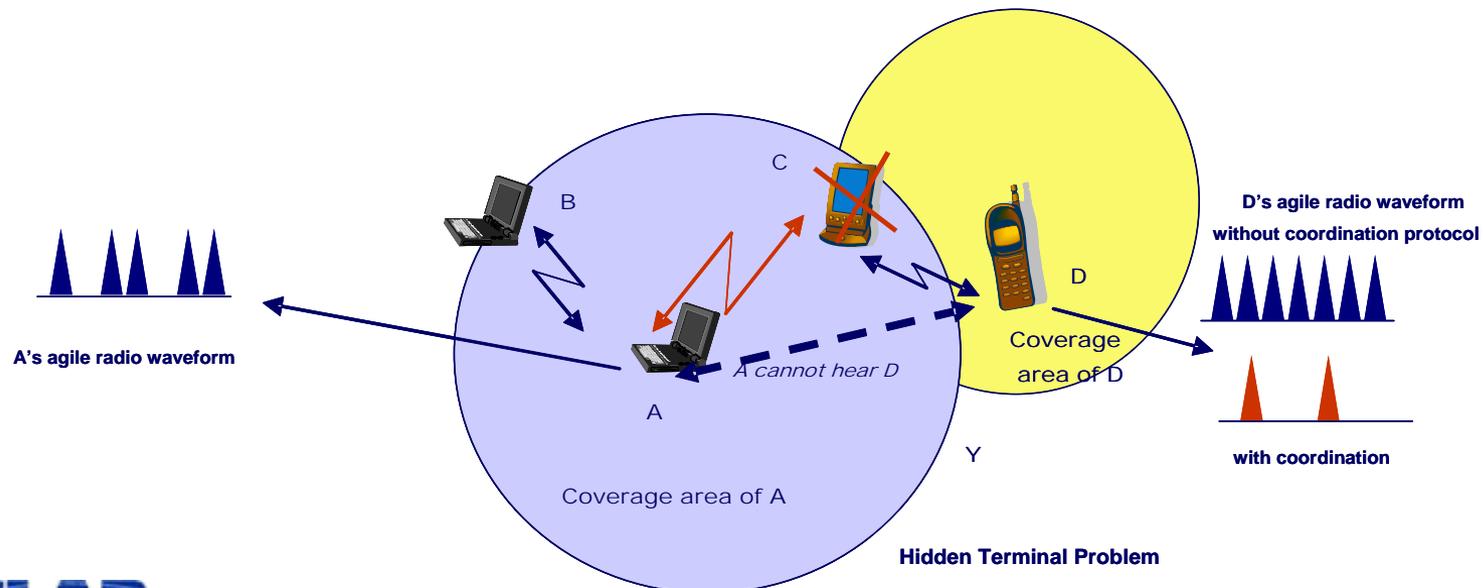
- **Negotiation strategies for mediation**
  - Pricing and microeconomic strategies to promote cooperation in spectrum sharing
  - Reimbursing costs in cooperation - energy costs, delay costs
- **Domination strategies for situations of conflict**
  - Spectrum warfare with agile waveforms and competition for spectrum
- **Coalition formation strategies for cooperation**
  - Coalitional games for receiver and transmitter coalitions in spectrum sharing

Approaches result in algorithms that specify:

- Power control
- Rate control
- Channel selection
- Cooperation techniques
- Route selection

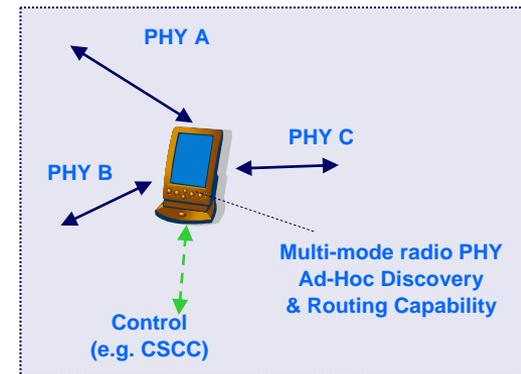
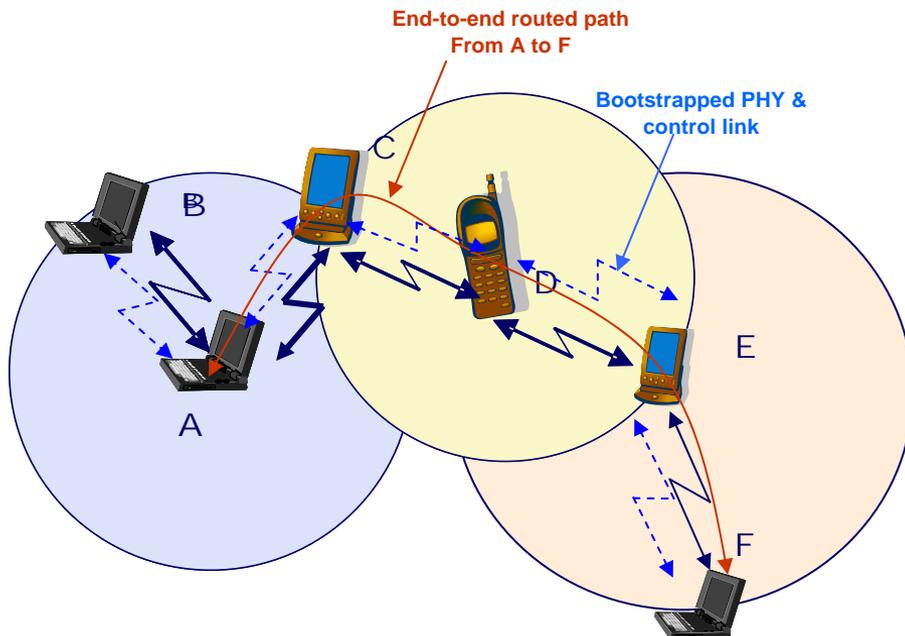
# PHY & MAC: Reactive Schemes

- Reactive (autonomous) methods used to avoid interference via:
  - Frequency agility: dynamic channel allocation by scanning
  - Power control: power control by interference detection and scanning
  - Time scheduling: MAC packet re-scheduling based on observed activity
  - Waveform agility: dynamism in signal space
- Reactive schemes (without explicit coordination protocols) have limitations: **Interference is a receiver property!**



# Cognitive Approaches: Outlook

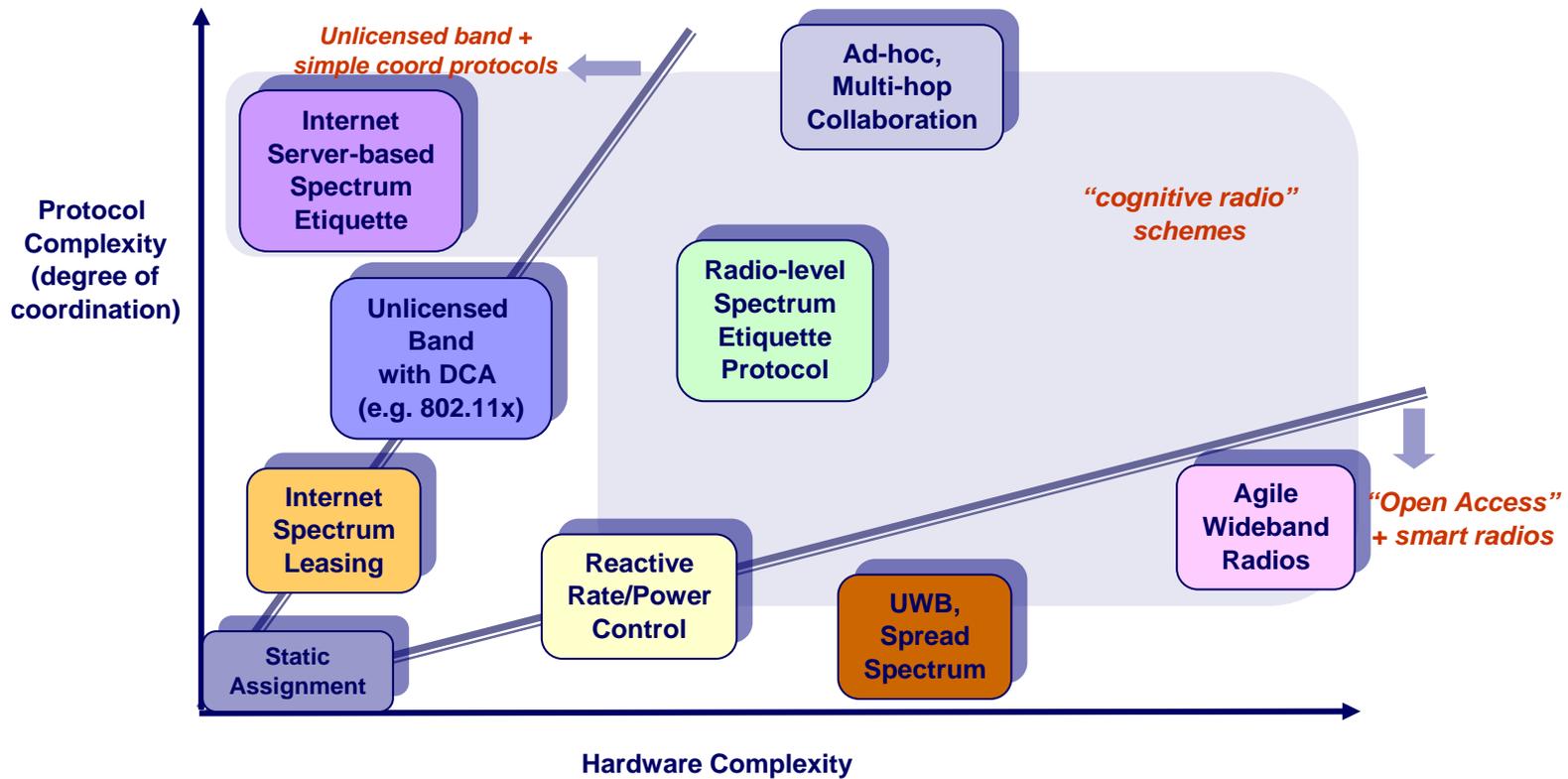
- Cognitive radio networks require a large amount of network (and channel) state information to enable efficient
  - Discovery
  - Self-organization
  - Cooperation Techniques



*Functionality can be quite challenging!*

# Cognitive Radio: Design Space

- Broad range of technology & related policy options for spectrum

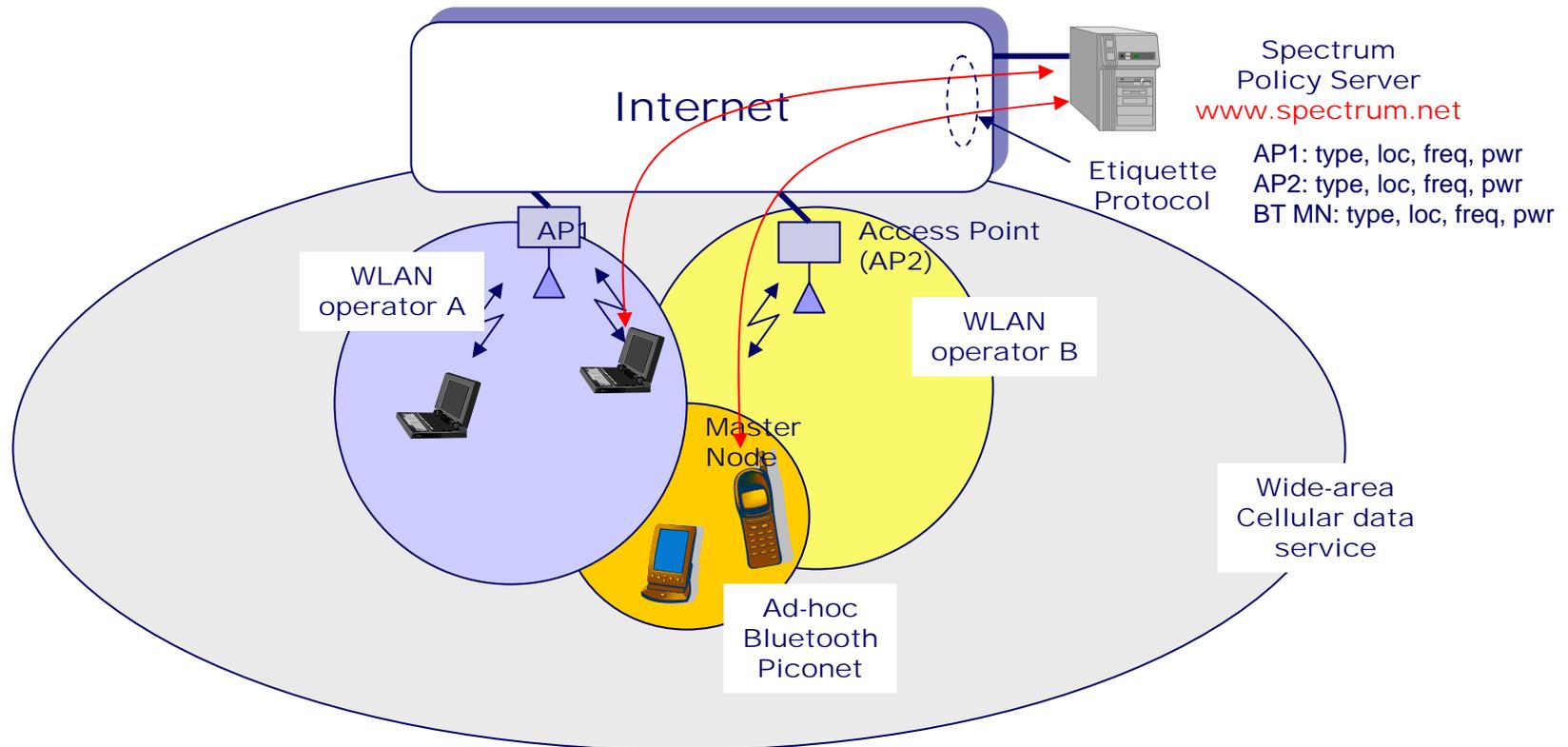


# Cognitive Radios need help too!

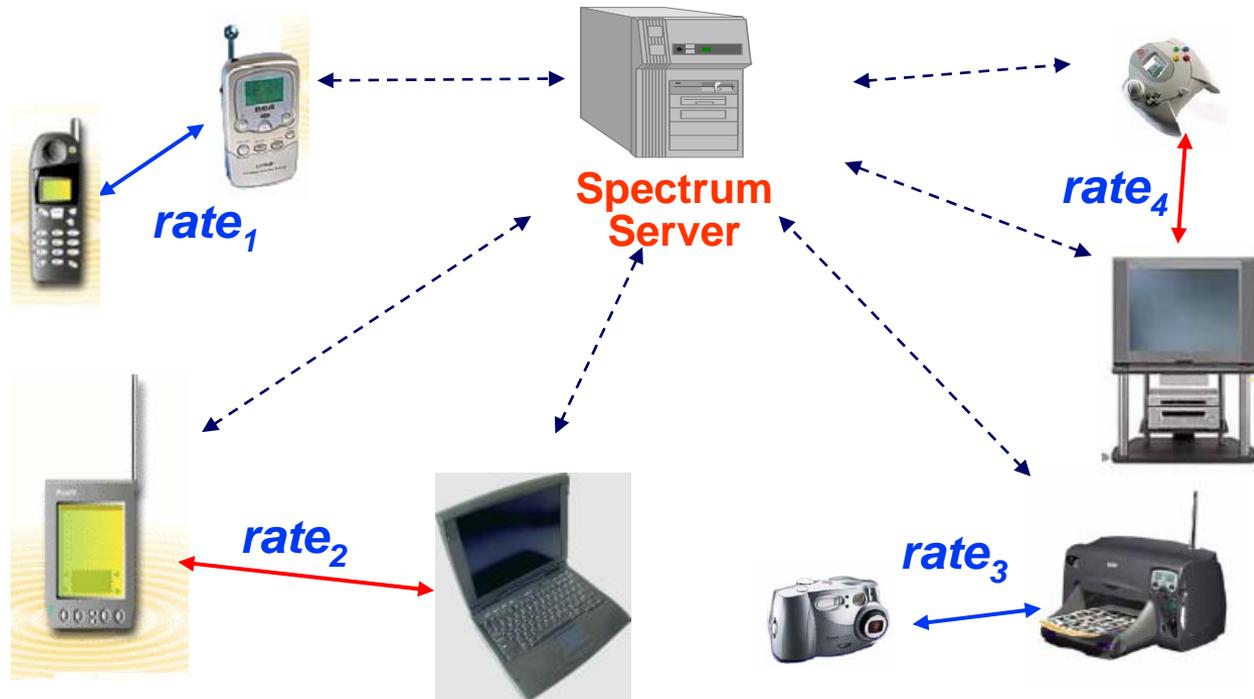
- Infrastructure that can facilitate cognitive radio networks
- Coordination mechanisms for coexistence and cooperation
  - Information aids
    - "Spectrum Coordination Channel" to enable spectrum sharing
  - Network architectures
    - "Spectrum Servers" to advise/mediate sharing

# Cognitive Radio: Spectrum Policy Server

- Internet-based Spectrum Policy Server can help to coordinate wireless networks (a "Google for spectrum")
  - Needs connection to Internet even under congested conditions (...low bit-rate OK)
  - Some level of position determination needed (...coarse location OK?)
  - Spectrum coordination achieved via etiquette protocol centralized at server



# What can a Spectrum Policy Server do?



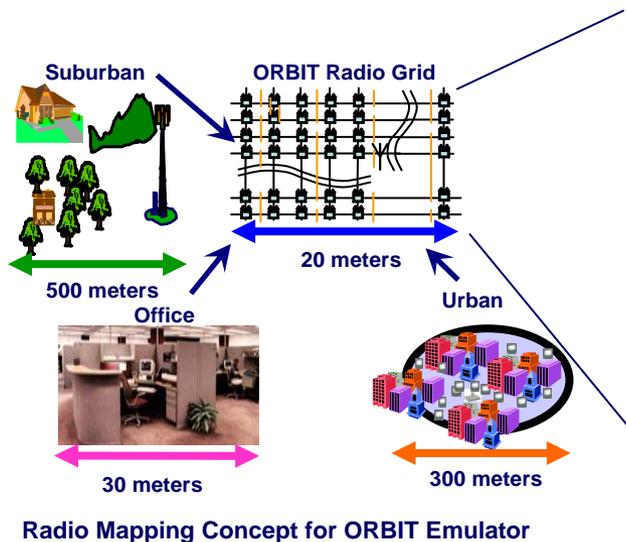
- Spectrum Policy Server facilitates co-existence of heterogeneous set of radios by advising them on several possible issues:

- Spectrum policy
- Interference information
- Scheduling and coexistence
- Location specific services
- Context

- Mobility Management
- Addressing
- Authentication
- Security
- Content

# Cognitive Radio Network Experiments Hardware/Software Platforms@WINLAB

- ORBIT radio grid testbed currently supports ~10/USRP GNU radios, 100 low-cost spectrum sensors, WARP platforms, WINLAB Cognitive platforms and GNU/USRP2
- Each platform will include baseline CogNet stack



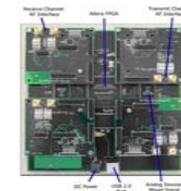
400-node Radio Grid Facility at WINLAB Tech Center



Current ORBIT sandbox with GNU radio

Programmable  
ORBIT radio node

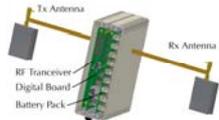
Planned upgrade  
(2007-08)



URSP2  
CR board

# Cognitive Radio in NSF's GENI Project

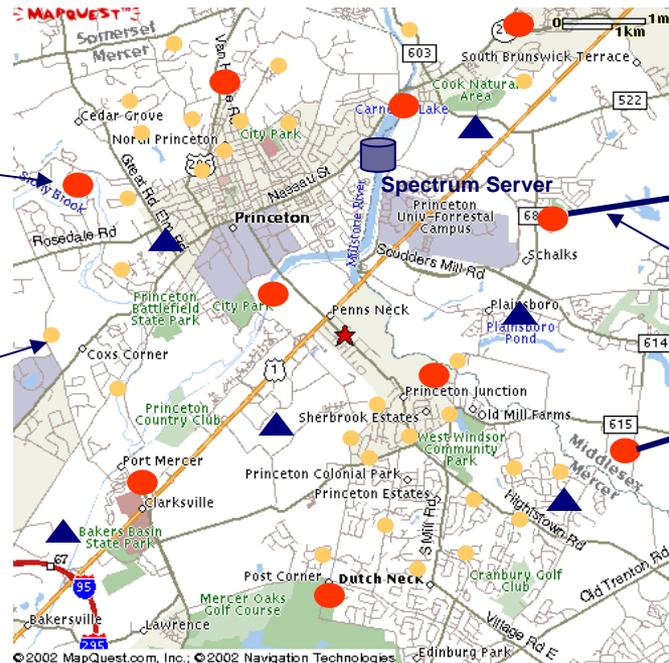
- Propose to build advanced technology demonstrator of cognitive radio networks for reliable wide-area services (over a ~50 Km\*\*2 coverage area) with spectrum sharing, adaptive networking, etc.
  - Basic building block is a cognitive radio platform, to be selected from competing research projects now in progress and/or future proposals
  - Requires enhanced software interfaces for control of radio PHY, discovery and bootstrapping, adaptive network protocols ..... suitable for protocol virtualization
  - FCC experimental license for new cognitive radio band



Cognitive Radio Network Node



Cognitive Radio Client



● Cognitive Radio Network Node

● Cognitive Radio Client

▲ Spectrum Monitors

Connections to GENI Infrastructure

### Research Focus:

1. New technology validation of cognitive radio
2. Protocols for adaptive PHY radio networks
3. Efficient spectrum sharing methods
4. Interference avoidance and spectrum etiquette
5. Dynamic spectrum measurement
6. Hardware platform performance studies