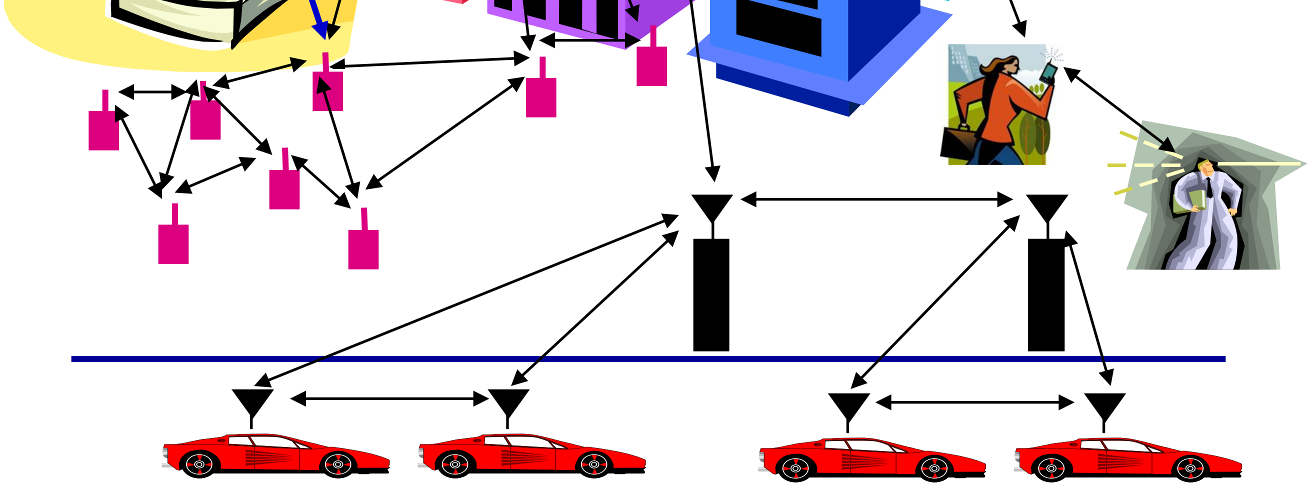
EE360: Lecture 18 Outline
Course Summary

- Announcements
  - Poster session tomorrow 5:30pm (3rd floor Packard)
  - Next HW posted, due March 19 at 9am
  - Final project due March 21 at midnight
  - Course evaluations available; worth 10 bonus points
- Course Summary
- Promising Research Directions

Course Summary

Future Wireless Networks

Ubiquitous Communication Among People and Devices



Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
In-Body Networks
All this and more …

Design Challenges

- Wireless channels are a difficult and capacity-limited broadcast communications medium
- Traffic patterns, user locations, and network conditions are constantly changing
- Applications are heterogeneous with hard constraints that must be met by the network
- Energy and delay constraints change design principles across all layers of the protocol stack

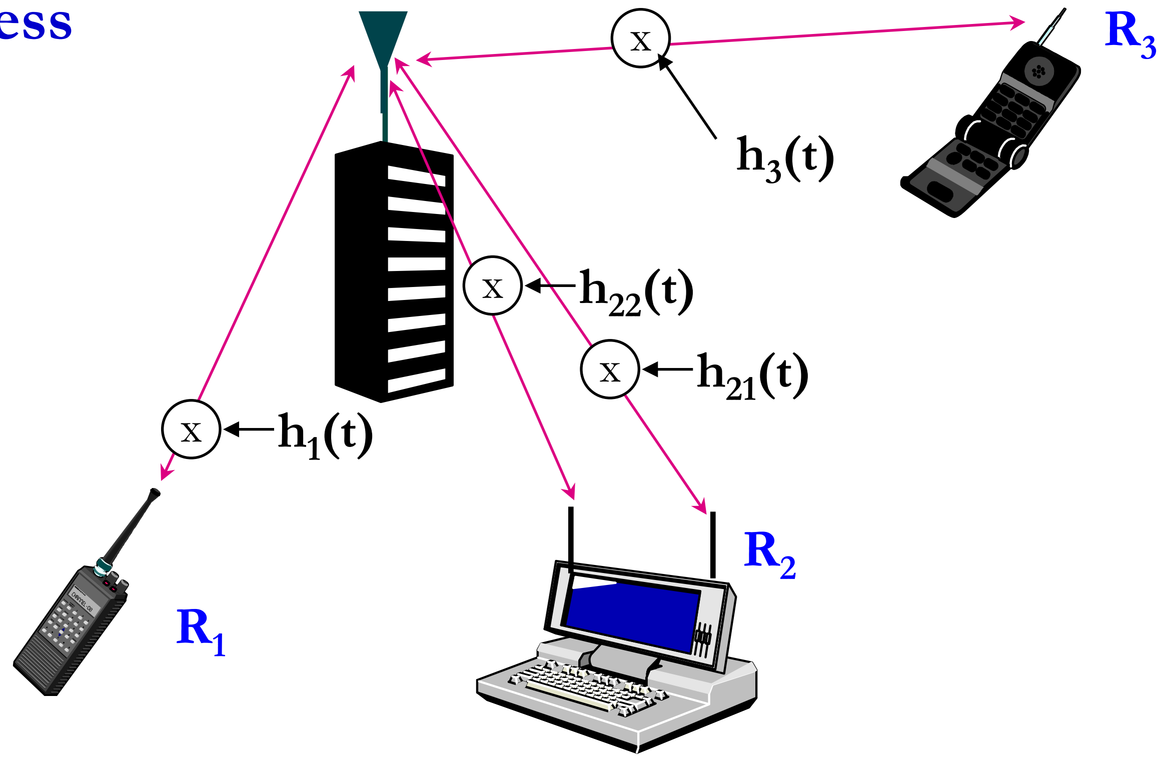
Wireless Network Design Issues

- Multiuser Communications
- Multiple and Random Access
- Cellular System Design
- Ad-Hoc and Cognitive Network Design
- Sensor Network Design
- Protocol Layering and Cross-Layer Design
- Network Optimization

Multiuser Channels: Uplink and Downlink

Uplink (Multiple Access Channel or MAC):
Many Transmitters to One Receiver.

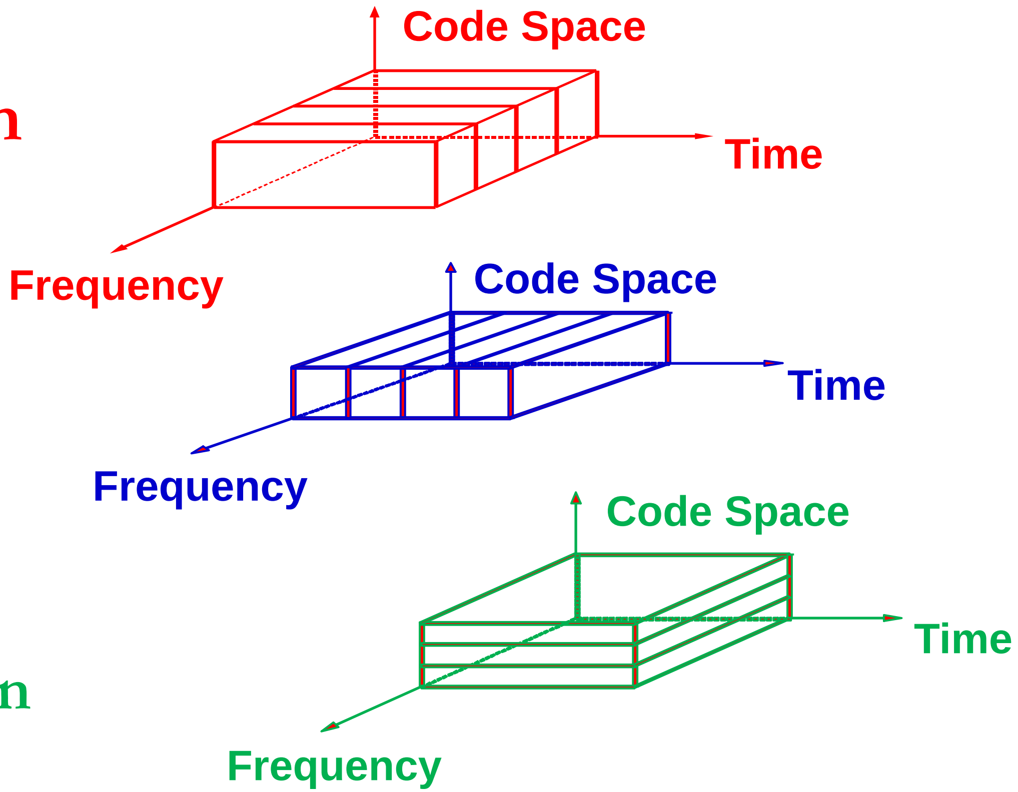
Downlink (Broadcast Channel or BC):
One Transmitter to Many Receivers.



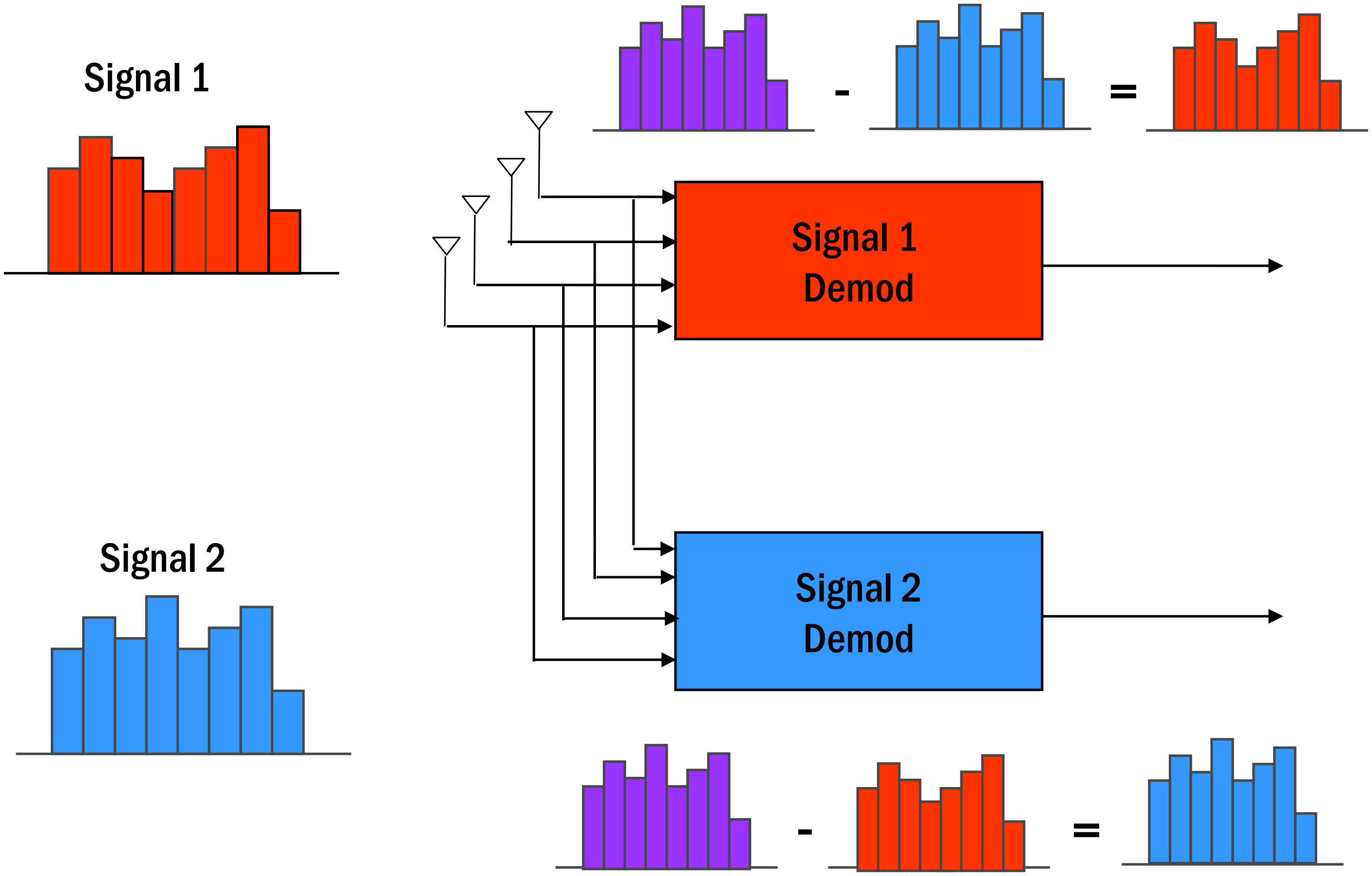
Uplink and Downlink typically duplexed in time or frequency

Bandwidth Sharing

- Frequency Division
- Time Division
- Code Division
  - Multiuser Detection
- Space (MIMO Systems)
- Hybrid Schemes



Multiuser Detection



Code properties of CDMA allow the signal separation and subtraction

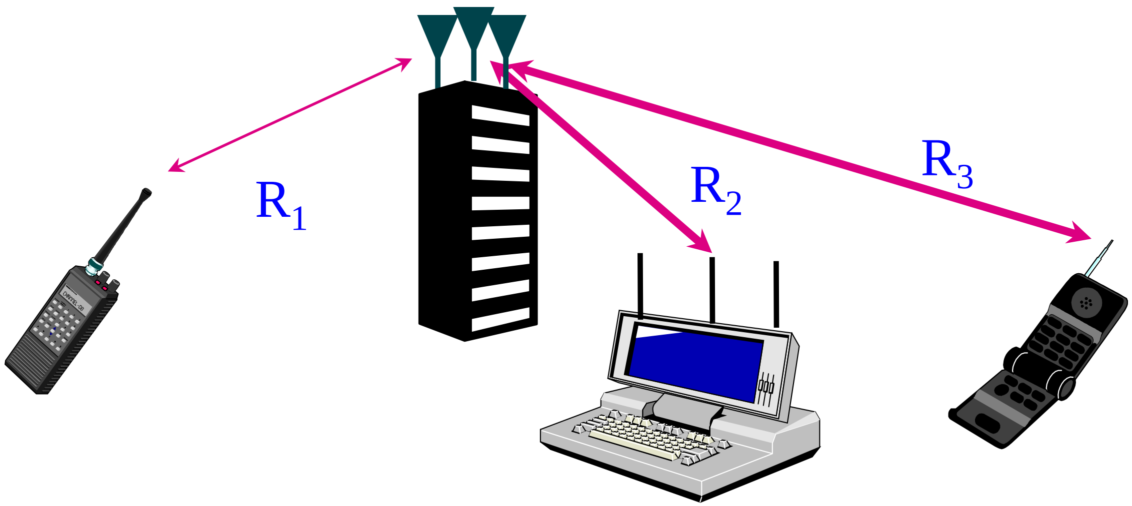
Random Access and Scheduling

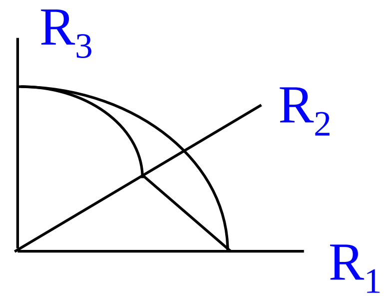
- Dedicated channels wasteful for data
  - Use statistical multiplexing
- Random Access Techniques
  - Aloha (Pure and Slotted)
  - Carrier sensing
    - Typically include collision detection or avoidance
  - Poor performance in heavy loading
- Reservation protocols
  - Resources reserved for short transmissions (overhead)
  - Hybrid Methods: Packet-Reservation Multiple Access
- Retransmissions used for corrupted data
  - Often assumes corruption due to a collision, not channel

Multiuser Channel Capacity

Fundamental Limit on Data Rates

Capacity: The set of simultaneously achievable rates $\{R_1,\ldots,R_n\}$

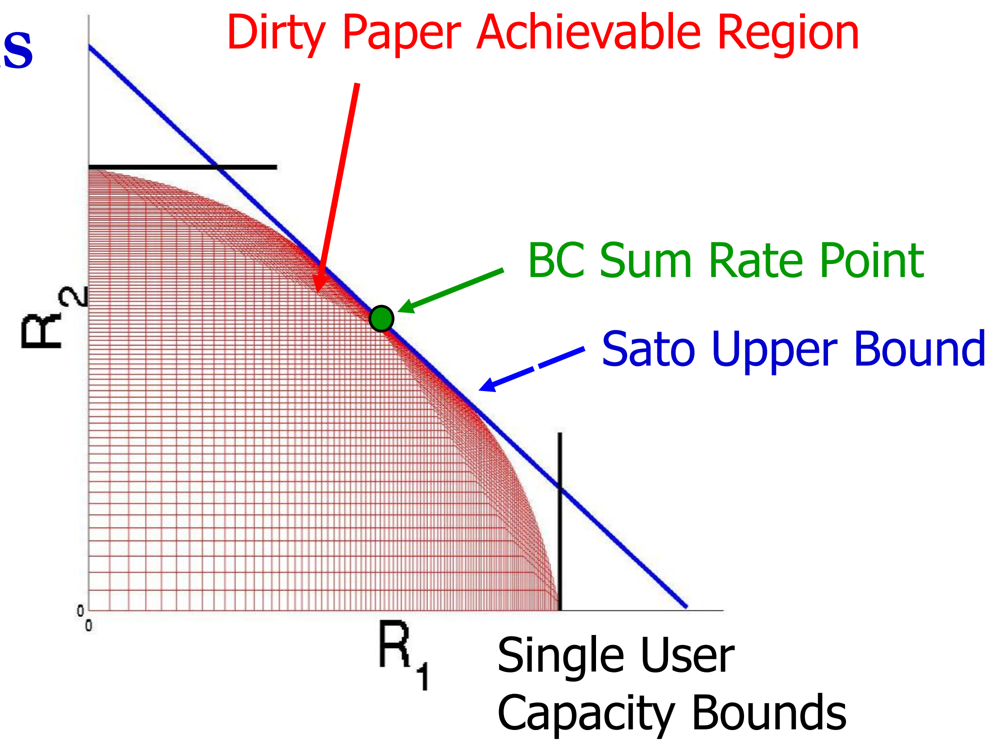




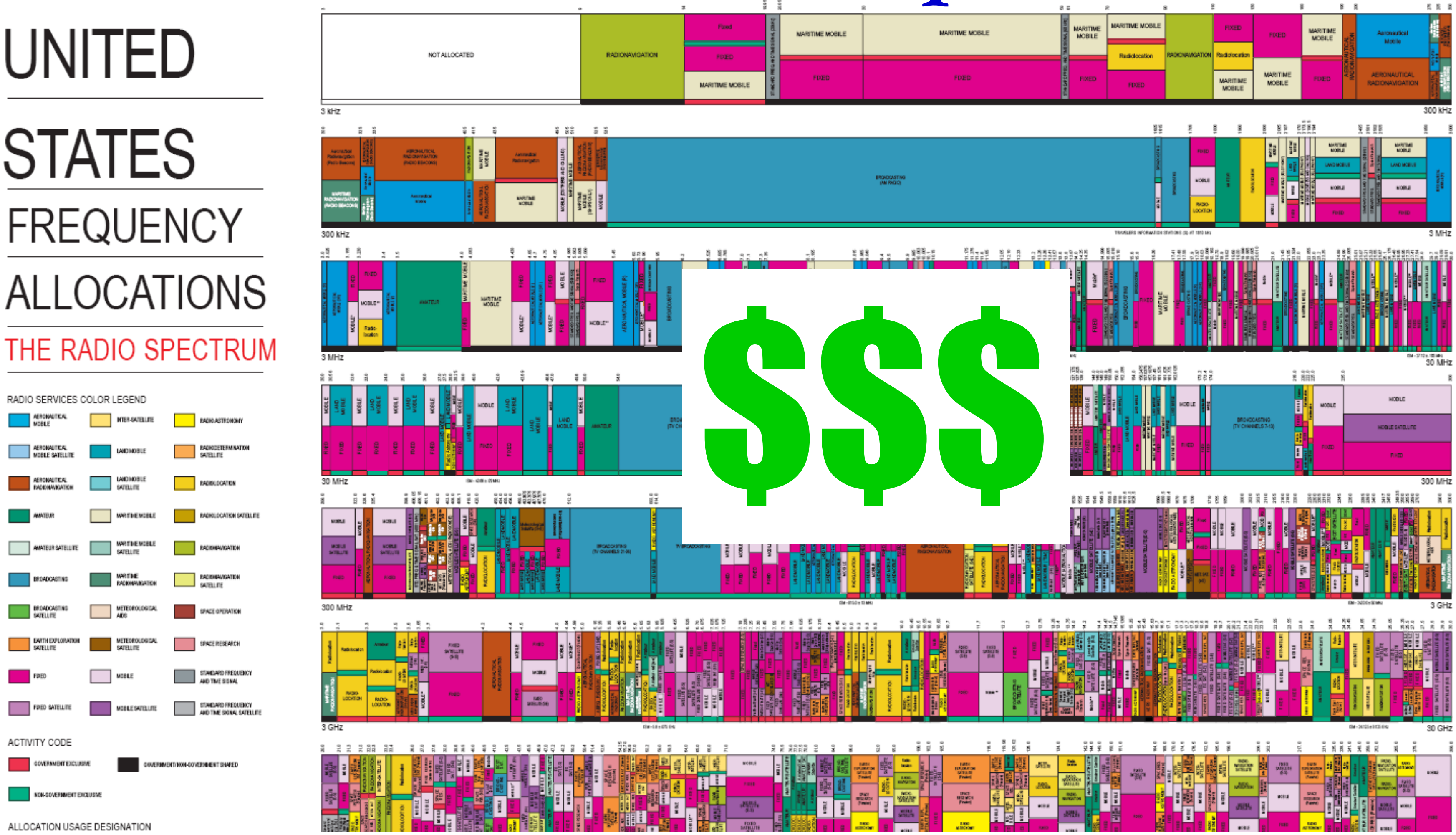
- **Main drivers of channel capacity**
  - **Bandwidth and received SINR**
  - **Channel model (fading, ISI)**
  - **Channel knowledge and how it is used**
  - **Number of antennas at TX and RX**
- **Duality connects capacity regions of uplink and downlink**

Capacity Results for Multiuser Channels

- Broadcast Channels
  - AWGN
  - Fading
  - ISI
- MACs
- Duality
- MIMO MAC and BC Capacity



Scarce Wireless Spectrum

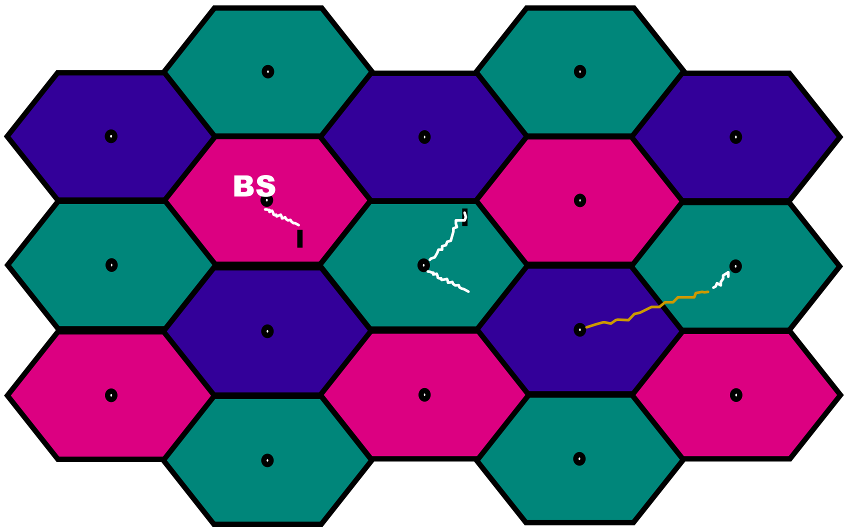


and Expensive

Spectral Reuse

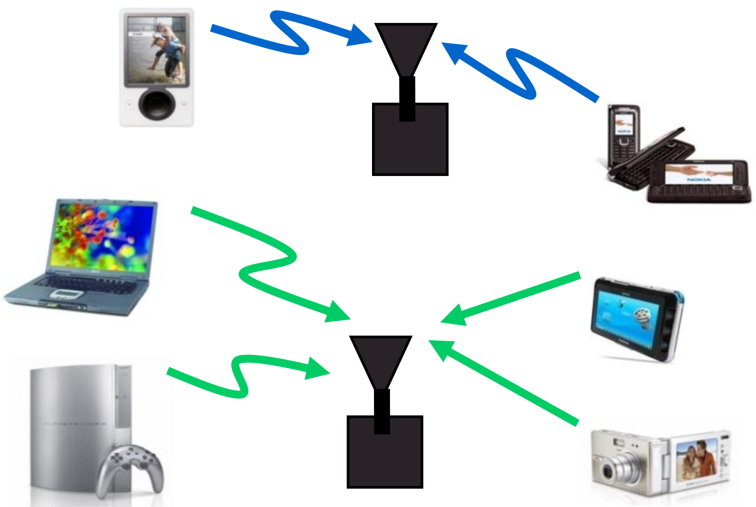
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular, Wimax

and unlicensed bands



Wifi, BT, UWB,…

Reuse introduces interference

Interference: *Friend or Foe?*

- If treated as noise: Foe

$$SNR = \frac{P}{N + I}$$

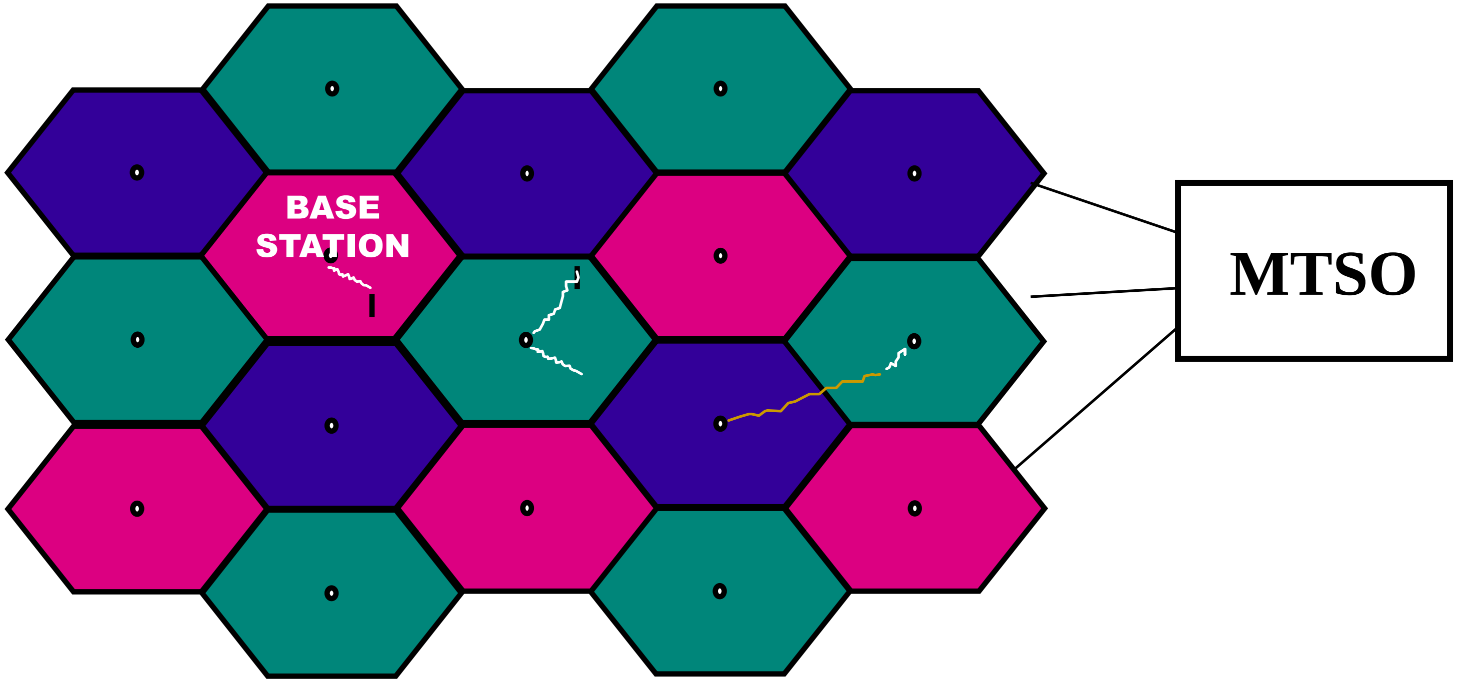
Increases BER
Reduces capacity

- If decodable (MUD): Neither friend nor foe

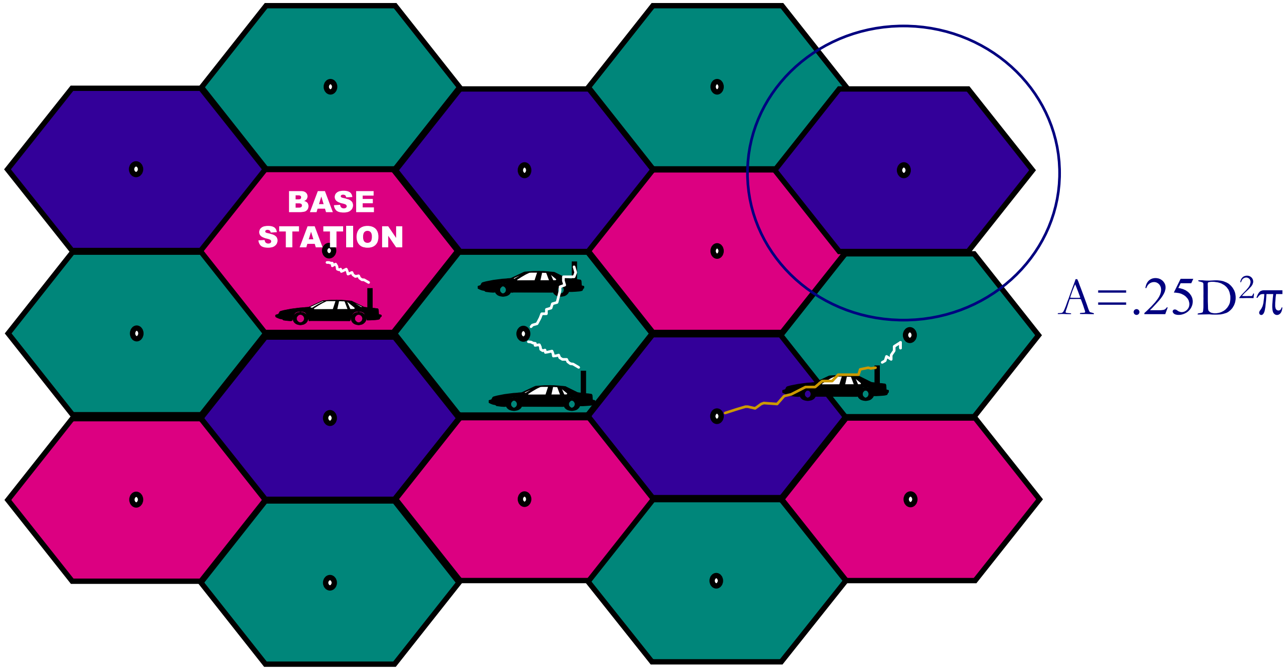
- If exploited via cooperation and cognition:
  Friend (especially in a network setting)

Cellular Systems
Reuse channels to maximize capacity

- 1G: Analog systems, large frequency reuse, large cells, uniform standard
- 2G: Digital systems, less reuse (1 for CDMA), smaller cells, multiple standards, evolved to support voice and data (IS-54, IS-95, GSM)
- 3G: Digital systems, WCDMA competing with GSM evolution.
- 4G: OFDM/MIMO



Area Spectral Efficiency



- S/I increases with reuse distance.
- For BER fixed, tradeoff between reuse distance and link spectral efficiency (bps/Hz).
- Area Spectral Efficiency: $A_e=\Sigma R_i/(.25D^2\pi)$ bps/Hz/Km^2.

Improving Capacity

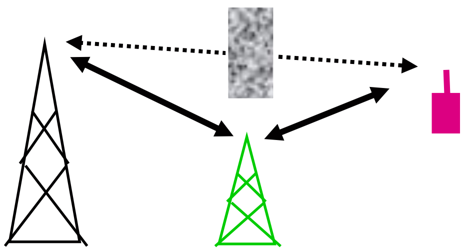
- Interference averaging
  - WCDMA (3G)
- Interference cancellation
  - Multiuser detection
- Interference reduction
  - Sectorization, smart antennas, and relaying
  - Dynamic resource allocation
  - Power control
- MIMO techniques
  - Space-time processing

Multiuser Detection in Cellular

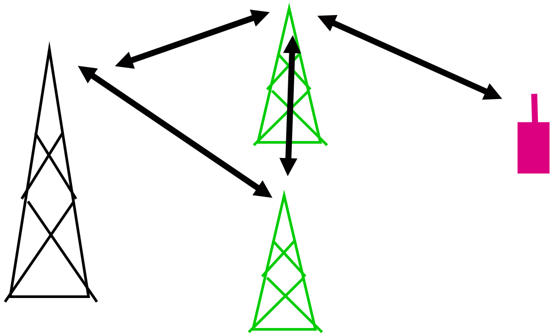
- Goal: decode interfering signals to remove them from desired signal
- Interference cancellation
  - decode strongest signal first; subtract it from the remaining signals
  - repeat cancellation process on remaining signals
  - works best when signals received at very different power levels
- Optimal multiuser detector (Verdu Algorithm)
  - cancels interference between users in parallel
  - complexity increases exponentially with the number of users
- Other techniques tradeoff performance and complexity
  - decorrelating detector
  - decision-feedback detector
  - multistage detector
- MUD often requires channel information; can be hard to obtain

Benefits of Relaying in Cellular Systems

- Power falls of exponentially with distance
  - Relaying extends system range
- Can eliminate coverage holes due to shadowing, blockage, etc.



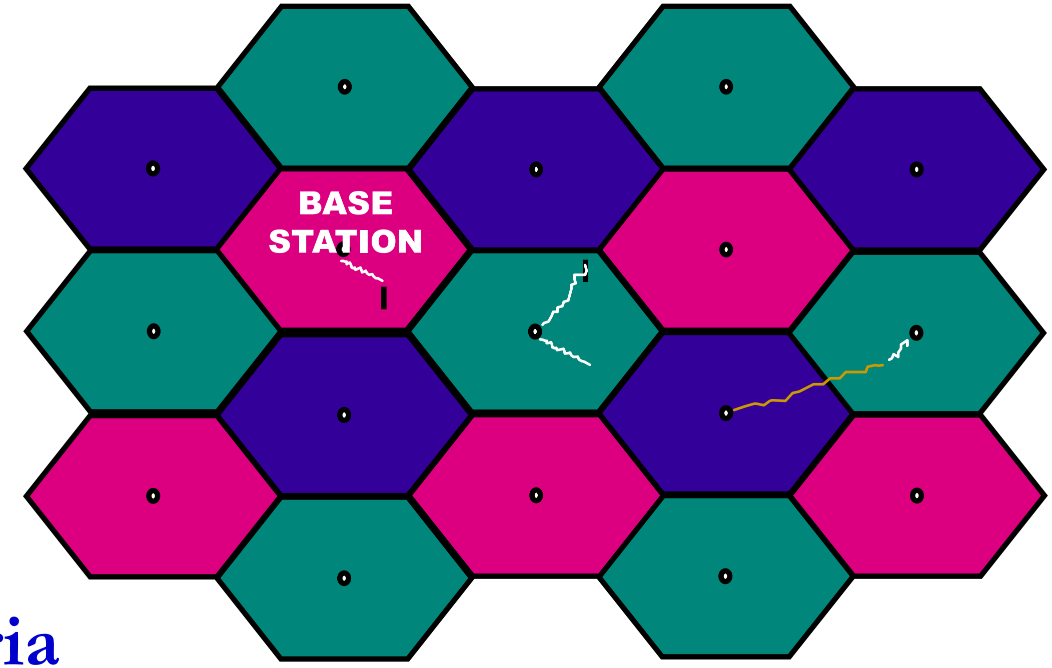
- Increases frequency reuse
  - Increases network capacity
- Virtual Antennas and Cooperation
  - Cooperating relays techniques
  - May require tight synchronization



Dynamic Resource Allocation

Allocate resources as user and network conditions change

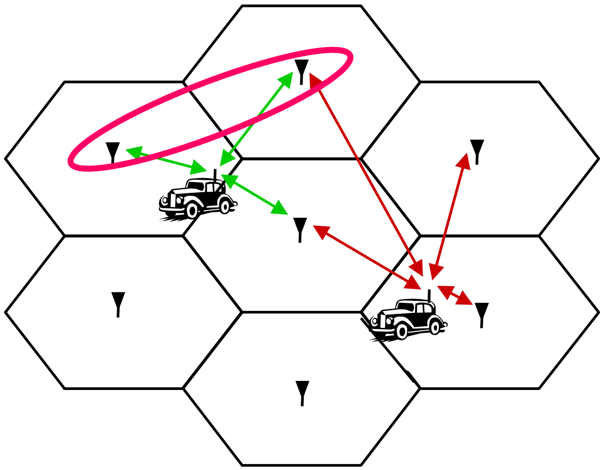
- Resources:
  - Channels
  - Bandwidth
  - Power
  - Rate
  - Base stations
  - Access



- Optimization criteria
  - Minimize blocking (voice only systems)
  - Maximize number of users (multiple classes)
  - Maximize "revenue"
    - Subject to some minimum performance for each user

"DCA is a 2G/4G problem"

MIMO Techniques in Cellular

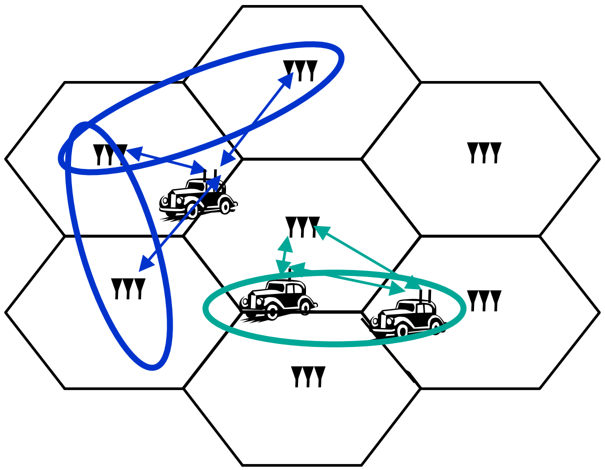


- How should MIMO be *fully* used in cellular systems?
- Network MIMO: Cooperating BSs form an antenna array
  - Downlink is a MIMO BC, uplink is a MIMO MAC
  - Can treat "interference" as known signal (DPC) or noise
- Multiplexing/diversity/interference cancellation tradeoffs
  - Can optimize receiver algorithm to maximize SINR

MIMO in Cellular: *Performance Benefits*

- Antenna gain ⇒ extended battery life, extended range, and higher throughput
- Diversity gain ⇒ improved reliability, more robust operation of services
- Interference suppression (TXBF) ⇒ improved quality, reliability, and robustness
- Multiplexing gain ⇒ higher data rates
- Reduced interference to other systems

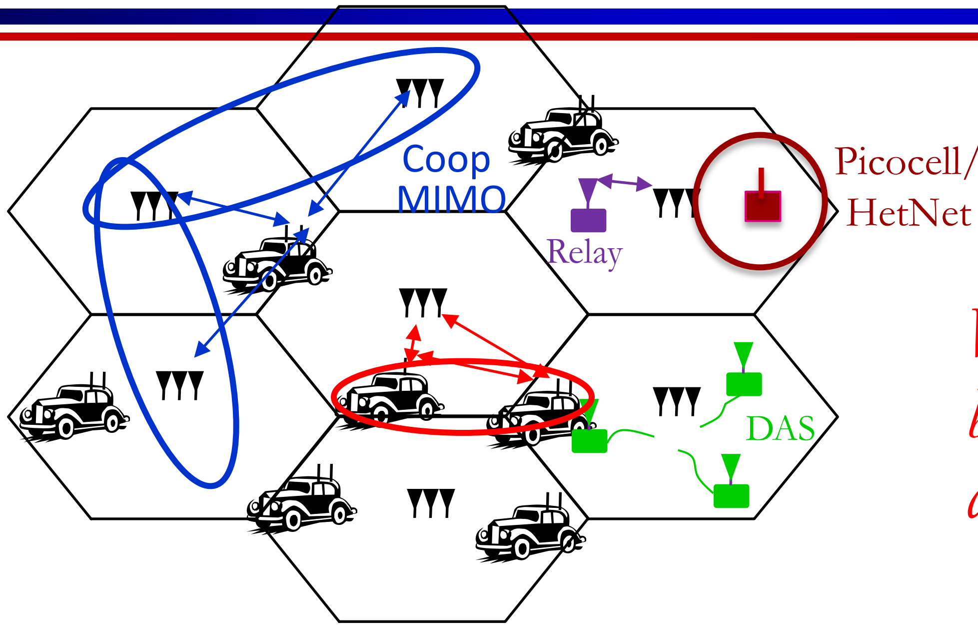
Cooperative Techniques in Cellular



Many open problems for next-gen systems

- Network MIMO: Cooperating BSs form a MIMO array
  - Downlink is a MIMO BC, uplink is a MIMO MAC
  - Can treat "interference" as known signal (DPC) or noise
  - Can cluster cells and cooperate between clusters
  - Can also install low-complexity relays
- Mobiles can cooperate via relaying, virtual MIMO, conferencing, analog network coding, …

Rethinking "Cells" in Cellular

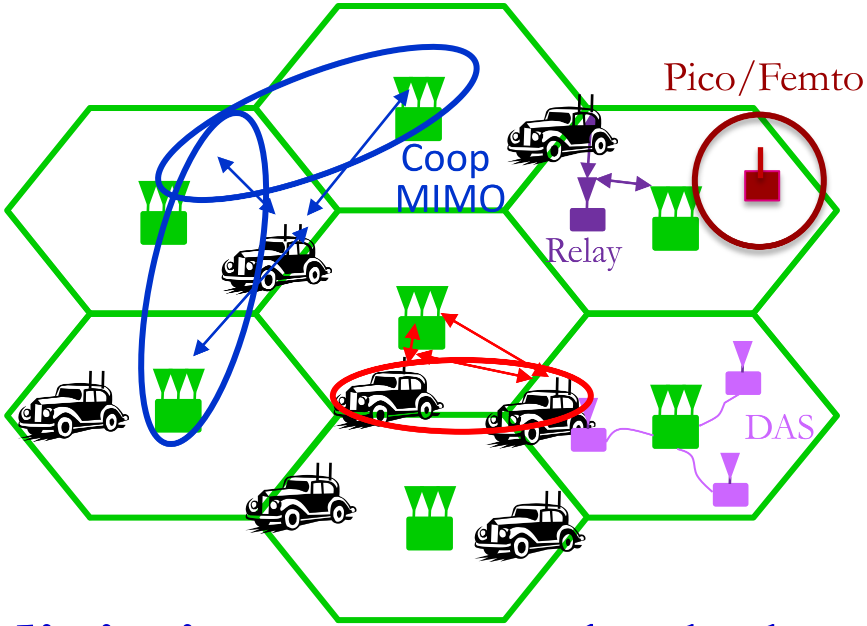


How should cellular systems be designed?

Will gains in practice be big or incremental; in capacity or coverage?

- **Traditional cellular design "interference-limited"**
  - **MIMO/multiuser detection can remove interference**
  - **Cooperating BSs form a MIMO array: what is a cell?**
  - **Relays change cell shape and boundaries**
  - **Distributed antennas move BS towards cell boundary**
  - **Small cells create a cell within a cell (HetNet)**
  - **Mobile cooperation via relaying, virtual MIMO, analog network coding.**

Green" Cellular Networks



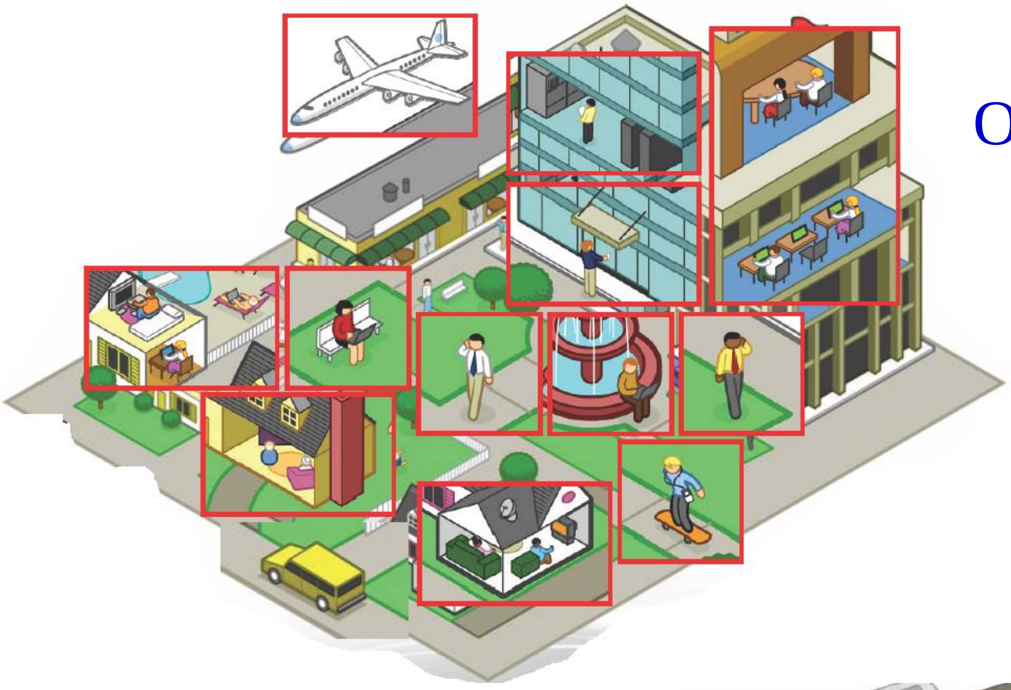
How should cellular systems be redesigned for minimum energy?

Research indicates that signicant savings is possible

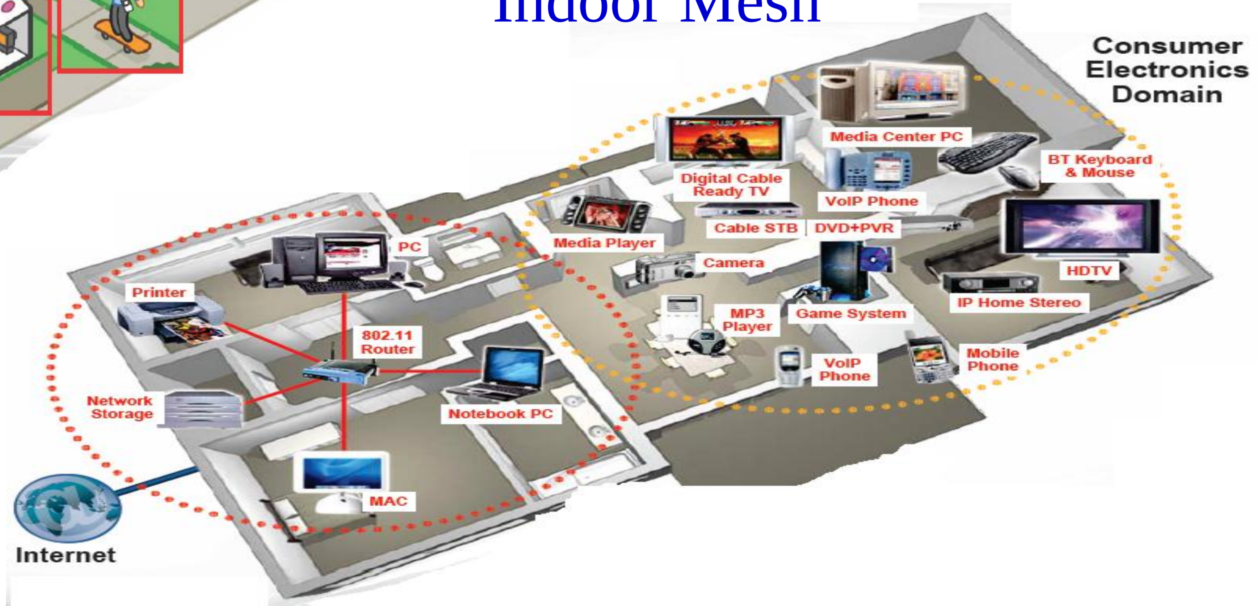
- **Minimize energy at both the mobile *and* base station via**
  - **New Infrastuctures: cell size, BS placement, DAS, Picos, relays**
  - **New Protocols: Cell Zooming, Coop MIMO, RRM, Scheduling, Sleeping, Relaying**
  - **Low-Power (Green) Radios: Radio Architectures, Modulation, coding, MIMO**

Ad-Hoc/Mesh Networks

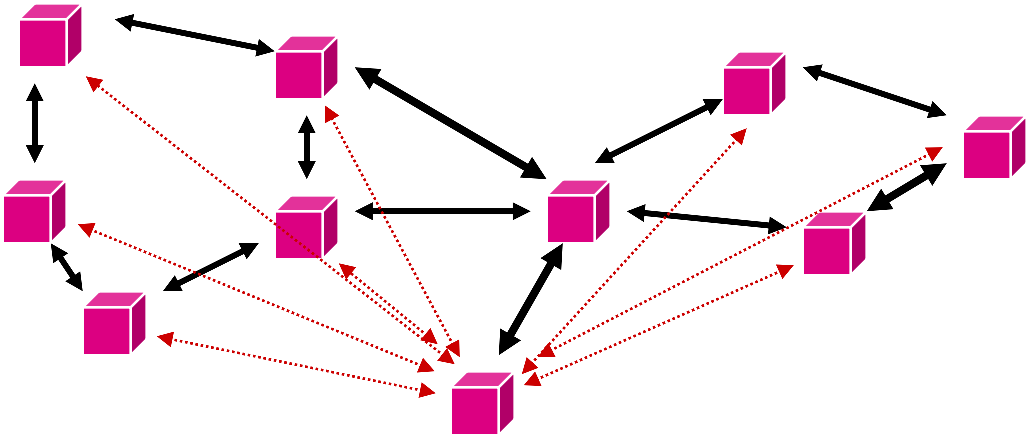
Outdoor Mesh



Indoor Mesh



Ad-Hoc Networks



- Peer-to-peer communications.
- No backbone infrastructure.
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs

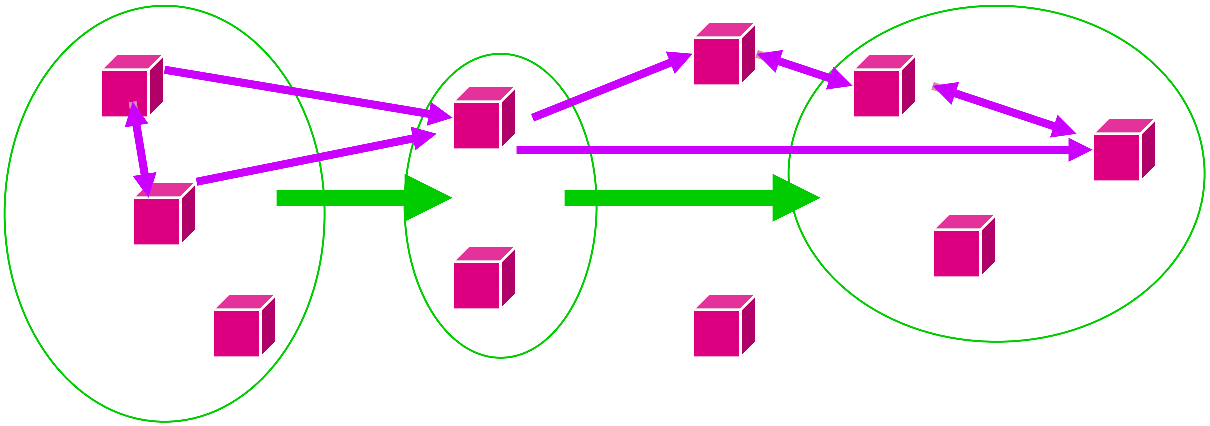
Design Issues

- Link layer design
- Channel access and frequency reuse
- Reliability
- Cooperation and Routing
- Adaptive Resource Allocation
- Network Capacity
- Cross Layer Design
- Power/energy management (Sensor Nets)

Routing Techniques

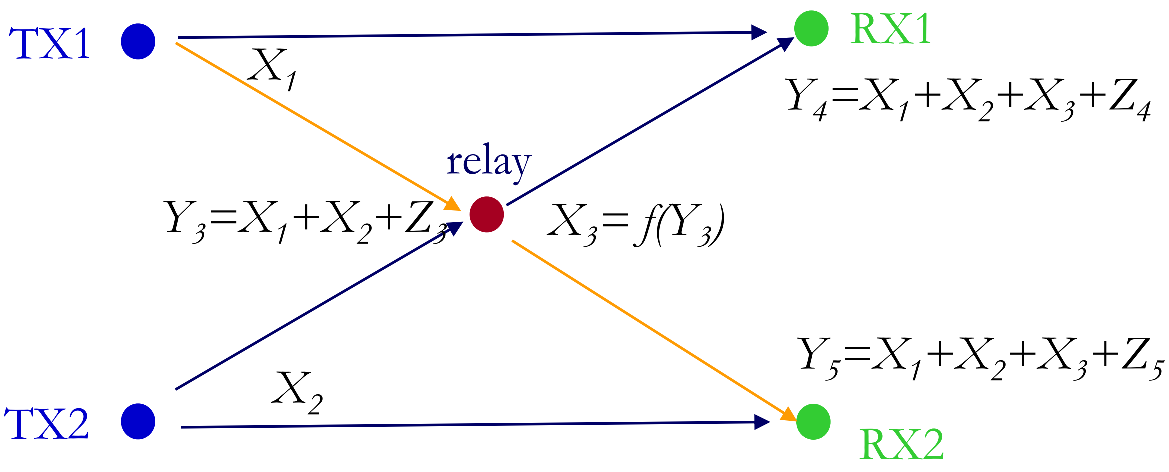
- Flooding
  - Broadcast packet to all neighbors
- Point-to-point routing
  - Routes follow a sequence of links
  - Connection-oriented or connectionless
- Table-driven
  - Nodes exchange information to develop routing tables
- On-Demand Routing
  - Routes formed “on-demand”
- Analog Network Coding

Cooperation in Ad-Hoc Networks



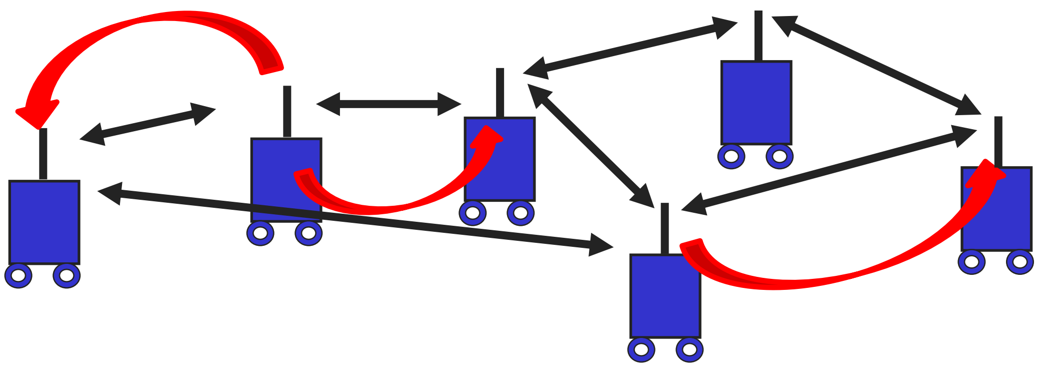
- **Many possible cooperation strategies:**
  - **Virtual MIMO , generalized relaying, interference forwarding, and one-shot/iterative conferencing**
- **Many theoretical and practice issues:**
  - **Overhead, forming groups, dynamics, synch, …**

Generalized Relaying



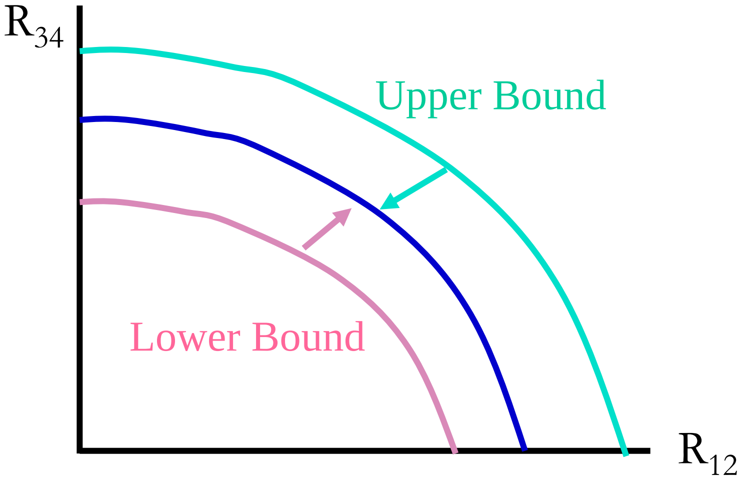
- Can forward message and/or interference
  - **Relay can forward all or part of the messages**
    - **Much room for innovation**
  - **Relay can forward interference**
    - **To help subtract it out**

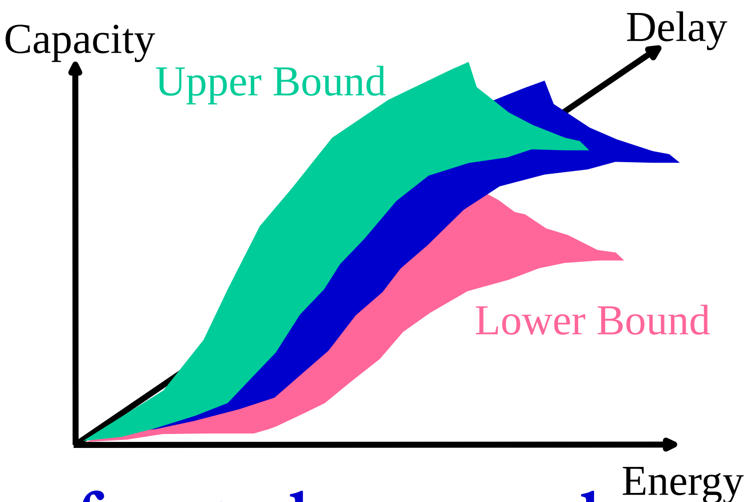
Adaptive Resource Allocation for Wireless Ad-Hoc Networks



- Network is dynamic (links change, nodes move around)
- Adaptive techniques can adjust to and exploit variations
- Adaptivity can take place at all levels of the protocol stack
- Negative interactions between layer adaptation can occur
- Network optimization techniques (e.g. NUM) often used
- Prime candidate for cross-layer design

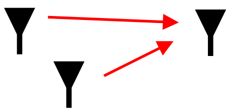
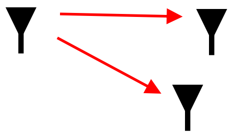
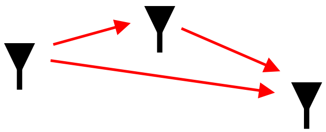
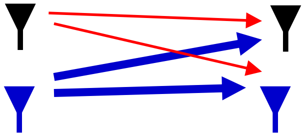
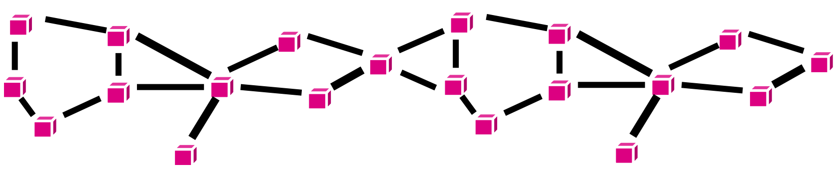
Ad-Hoc Network Capacity





- Network capacity in general refers to how much data a network can carry
- Multiple definitions
  - Shannon capacity: n(n-1)-dimensional region
  - Total network throughput (vs. delay)
  - User capacity (bps/Hz/user or total no. of users)
  - Other dimensions: delay, energy, etc.

Network Capacity Results

- Multiple access channel (MAC) 
- Broadcast channel 
- Relay channel upper/lower bounds 
- Interference channel 
- Scaling laws 
- Achievable rates for small networks

Intelligence beyond Cooperation: *Cognition*

- Cognitive radios can support new wireless users in existing crowded spectrum
  - Without degrading performance of existing users
- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies
- Technology could
  - Revolutionize the way spectrum is allocated worldwide
  - Provide sufficient bandwidth to support higher quality and higher data rate products and services

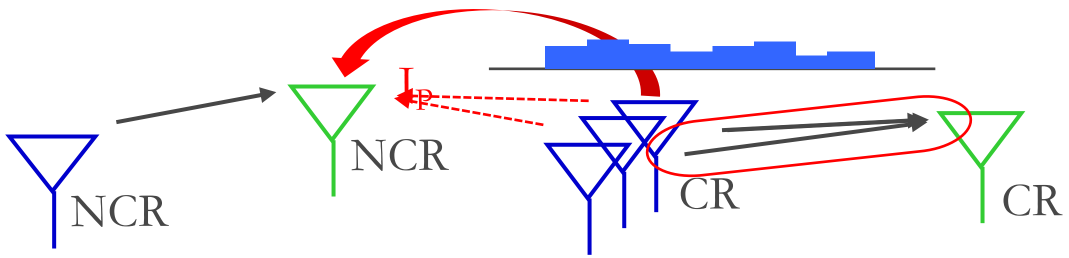
Cognitive Radio Paradigms

- Underlay
  - Cognitive radios constrained to cause minimal interference to noncognitive radios
- Interweave
  - Cognitive radios find and exploit spectral holes to avoid interfering with noncognitive radios
- Overlay
  - Cognitive radios overhear and enhance noncognitive radio transmissions

Knowledge and Complexity

Underlay Systems

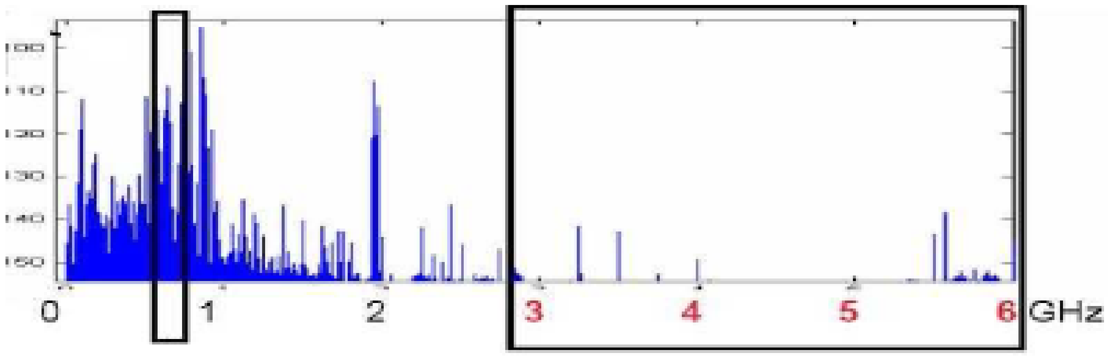
- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold



- The interference constraint may be met
  - Via wideband signalling to maintain interference below the noise floor (spread spectrum or UWB)
  - Via multiple antennas and beamforming

Interweave Systems

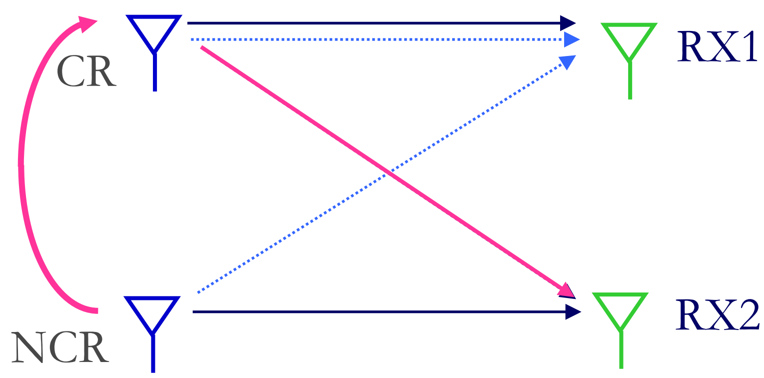
- Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies
  - Original motivation for “cognitive” radios (Mitola’00)



- These holes can be used for communication
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication with minimal interference to noncognitive users

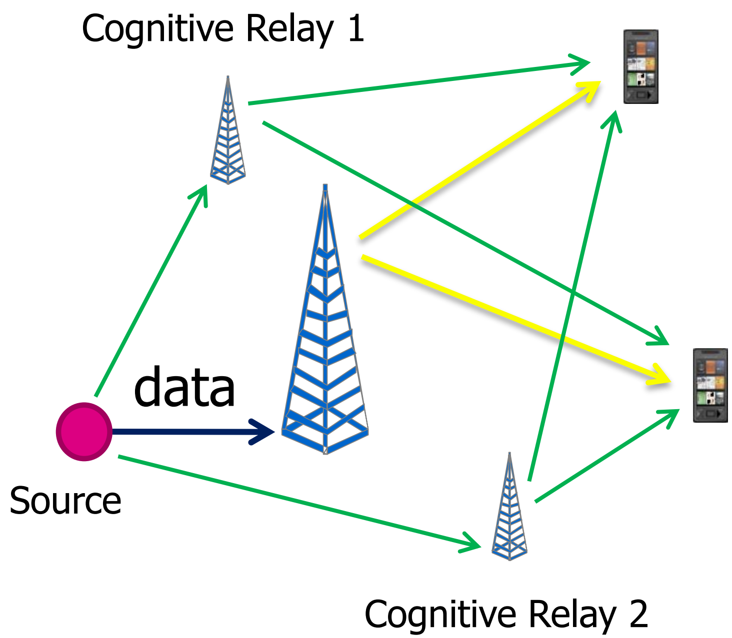
Overlay Systems

- Cognitive user has knowledge of other user's message and/or encoding strategy
  - Used to help noncognitive transmission
  - Used to presubtract noncognitive interference



  - Capacity/achievable rates known in some cases
    - With and without MIMO nodes

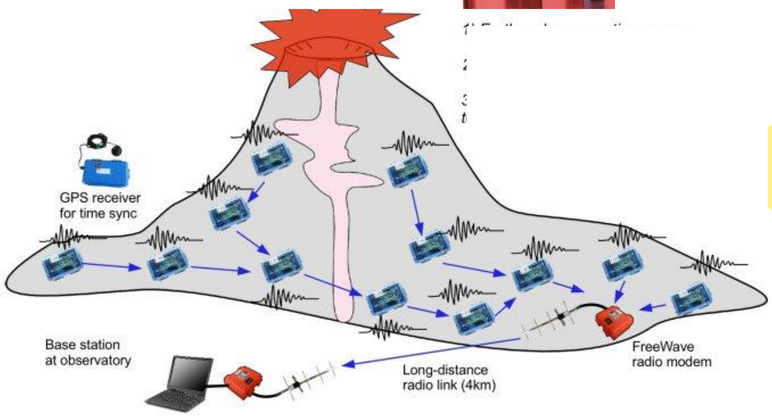
Cellular Systems with Cognitive Relays

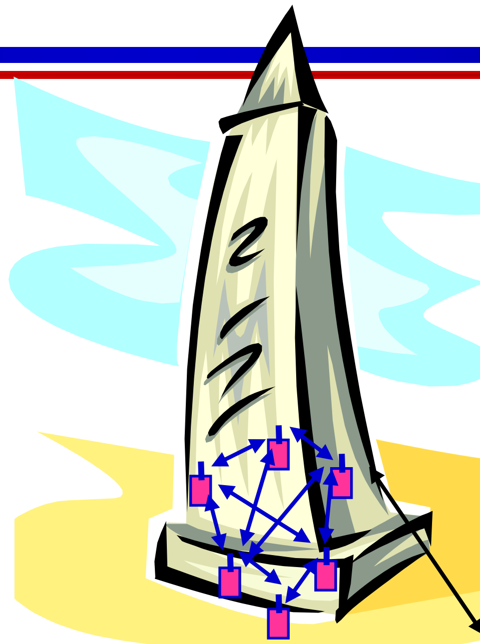


- Enhance robustness and capacity via cognitive relays
  - Cognitive relays overhear the source messages
  - Cognitive relays then cooperate with the transmitter in the transmission of the source messages
  - Can relay the message even if transmitter fails due to congestion, etc.

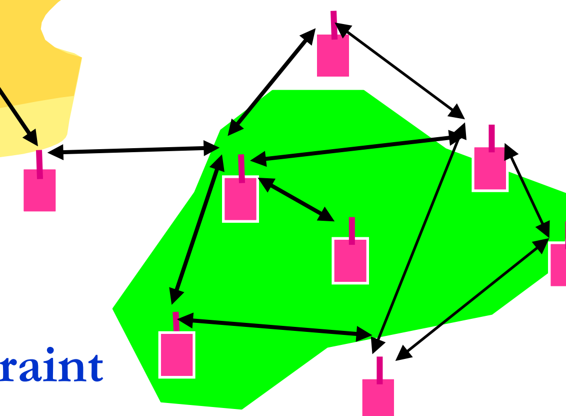
Can extend these ideas to MIMO systems

Wireless Sensor and "Green" Networks





- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance



- Energy (transmit and processing) is driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices
- Similar ideas can be used to re-architect systems and networks to be green

Energy-Constrained Nodes

- Each node can only send a finite number of bits.
  - Transmit energy minimized by maximizing bit time
  - Circuit energy consumption increases with bit time
  - Introduces a delay versus energy tradeoff for each bit
- Short-range networks must consider transmit, circuit, and processing energy.
  - Sophisticated techniques not necessarily energy-efficient.
  - Sleep modes save energy but complicate networking.
- Changes everything about the network design:
  - Bit allocation must be optimized across all protocols.
  - Delay vs. throughput vs. node/network lifetime tradeoffs.
  - Optimization of node cooperation.

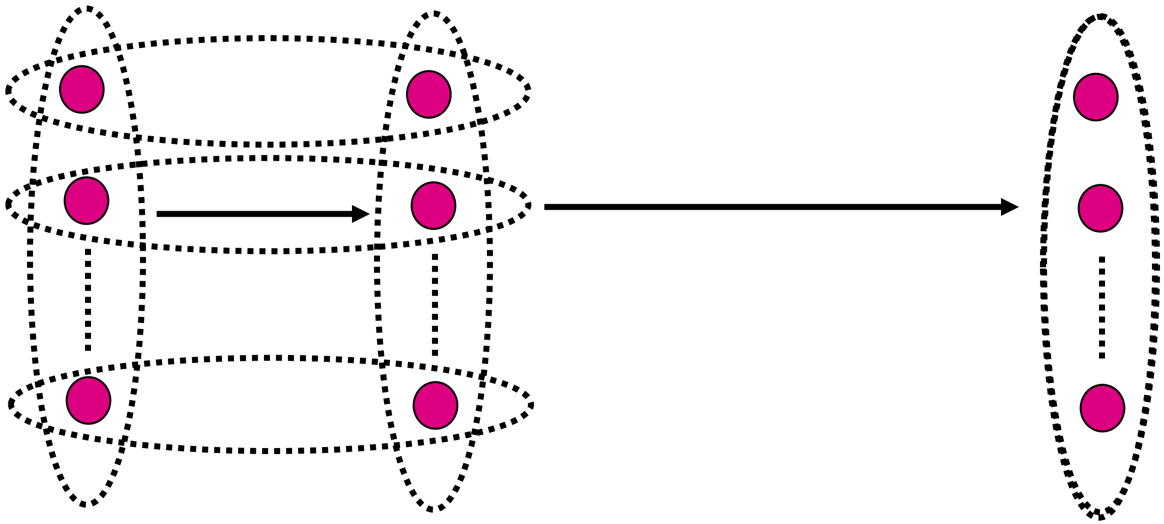
Cross-Layer Tradeoffs under Energy Constraints

- Hardware
  - Models for circuit energy consumption highly variable
  - All nodes have transmit, sleep, and transient modes
  - Short distance transmissions require TD optimization
- Link
  - High-level modulation costs transmit energy but saves circuit energy (shorter transmission time)
  - Coding costs circuit energy but saves transmit energy
- Access
  - Transmission time (TD) for all nodes jointly optimized
  - Adaptive modulation adds another degree of freedom
- Routing:
  - Circuit energy costs can preclude multihop routing
- Applications, cross-layer design, and in-network processing
  - Protocols driven by application reqmts (e.g. directed diffusion)

Application Domains

- **Home networking:** Smart appliances, home security, smart floors, smart buildings
- **Automotive:** Diagnostics, occupant safety, collision avoidance
- **Industrial automation:** Factory automation, hazardous material control
- **Traffic management:** Flow monitoring, collision avoidance
- **Security:** Building/office security, equipment tagging, homeland security
- **Environmental monitoring:** Habitat monitoring, seismic activity, local/global environmental trends, agricultural

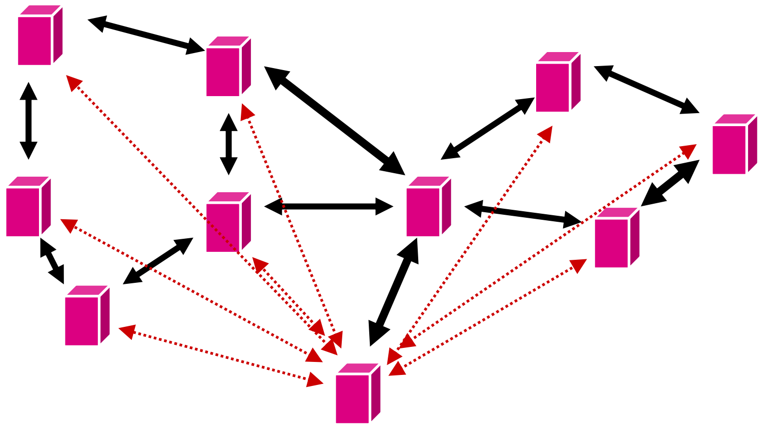
Cooperative Compression in Sensor Networks



- Source data correlated in space and time
- Nodes should cooperate in compression as well as communication and routing
  - Joint source/channel/network coding
  - What is optimal for cooperative communication:
    - Virtual MIMO or relaying?

Crosslayer Design in Wireless Networks

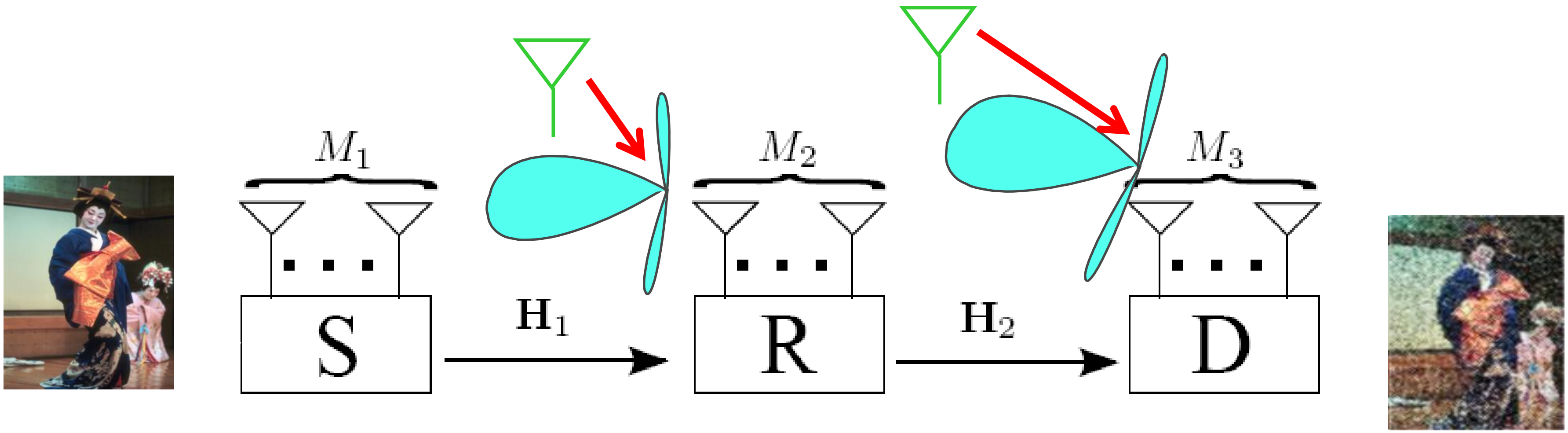
- Application
- Network
- Access
- Link
- Hardware



Tradeoffs at all layers of the protocol stack are optimized with respect to end-to-end performance

This performance is dictated by the application

Example: Image/video transmission over a MIMO multihop network



- Antennas can be used for multiplexing, diversity, or interference cancellation
    - M-fold possible capacity increase via multiplexing
    - M^2 possible diversity gain
    - Can cancel M-1 interferers
    - Errors occur due to fading, interference, and delay
- What metric should be optimized? Image "quality"

Promising Research Areas

Promising Research Areas

- Link Layer
  - Wideband air interfaces and dynamic spectrum management
  - Practical MIMO techniques (modulation, coding, imperfect CSI)
- Multiple/Random Access
  - Distributed techniques
  - Multiuser Detection
  - Distributed random access and scheduling
- Cellular Systems
  - How to use multiple antennas
  - Multihop routing
  - Cooperation
- Ad Hoc Networks
  - How to use multiple antennas
  - Cross-layer design

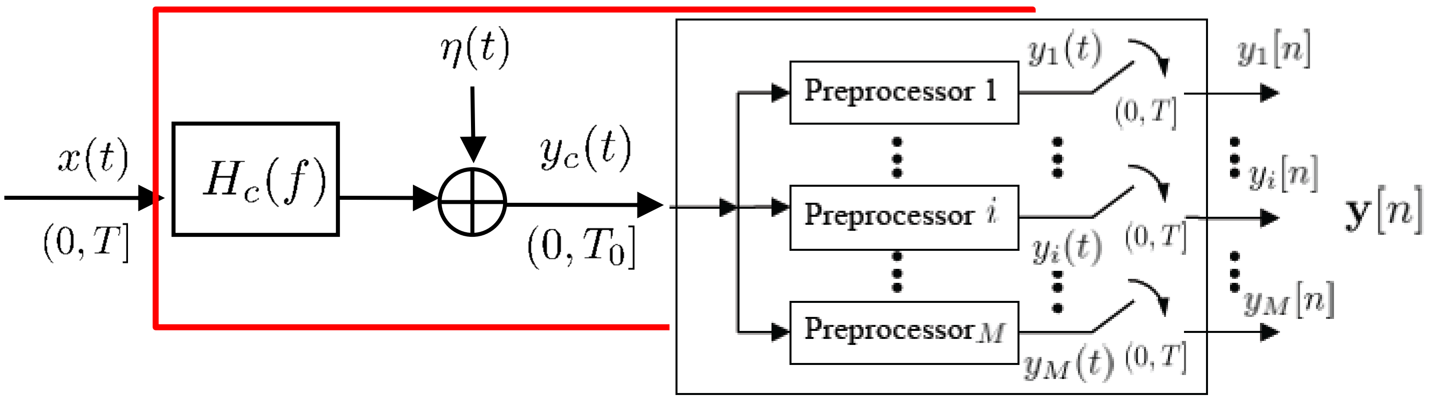
Promising Research Areas

- Cognitive Radio Networks
  - MIMO underlay systems – exploiting null space
  - Distributed detection of spectrum holes
  - Practice overlay techniques and applications
- Sensor networks
  - Energy-constrained communication
  - Cooperative techniques
- Information Theory
  - Capacity of ad hoc networks
  - Imperfect CSI
  - Incorporating delay: Rate distortion theory for networks
  - Applications in biology and neuroscience

Reduced-Dimension Communication System Design

- Compressed sensing ideas have found widespread application in signal processing and other areas.
- Basic premise of CS: exploit sparsity to approximate a high-dimensional system/signal in a few dimensions.
- Can sparsity be exploited to reduce the complexity of communication system design in general

Capacity of Sampled Analog Channels



- For a given sampling mechanism (i.e. a "new" channel)
  - What is the optimal input signal?
  - What is the *tradeoff* between capacity and sampling rate?
- What is the *optimal* sampling mechanism?
- Extensions to multiuser systems, MIMO, networks,…

Joint Optimization of Input and Filter Bank

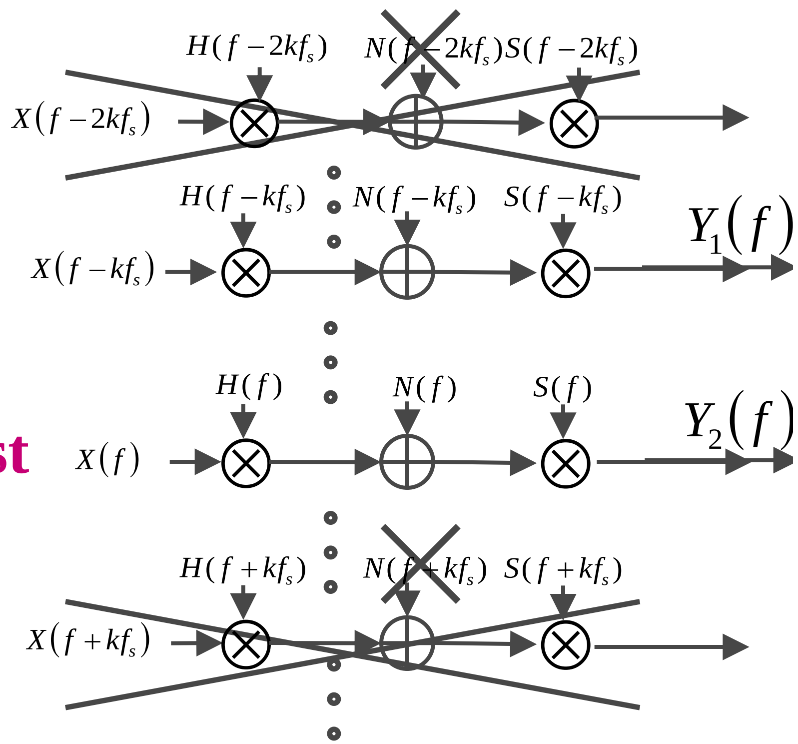
- Selects the ***m*** branches with ***m*** highest SNR
  - Example (Bank of 2 branches)

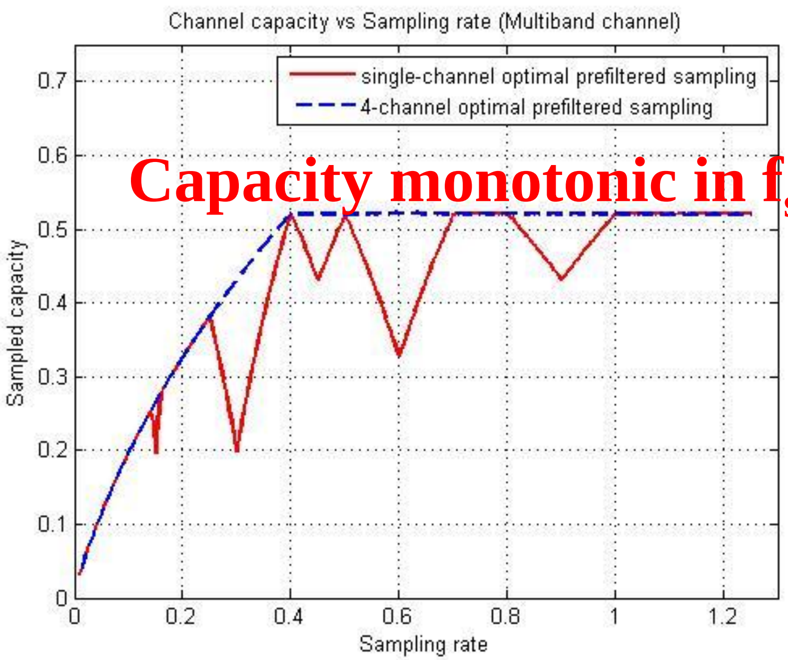
low SNR

highest SNR

2nd highest SNR

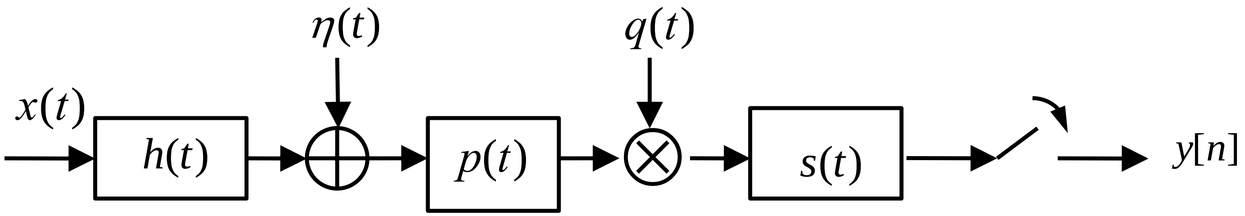
low SNR



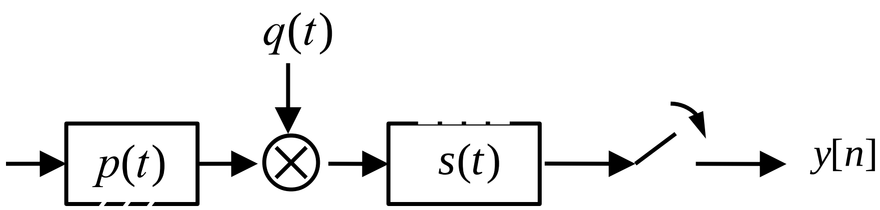


Capacity monotonic in f_s

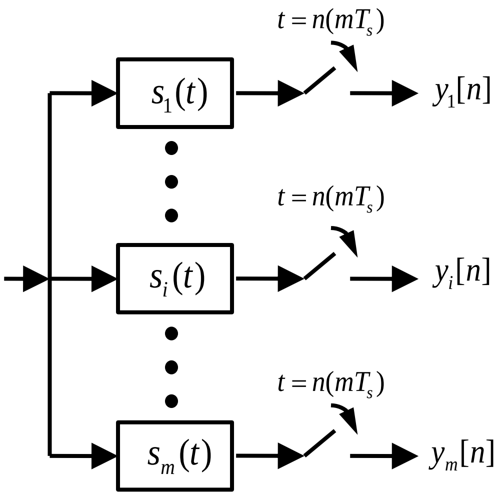
Sampling with Modulator and Filter Bank



- **Theorem:**
  - Bank of Modulator+Filter≅Single Branch ≅ Filter Bank

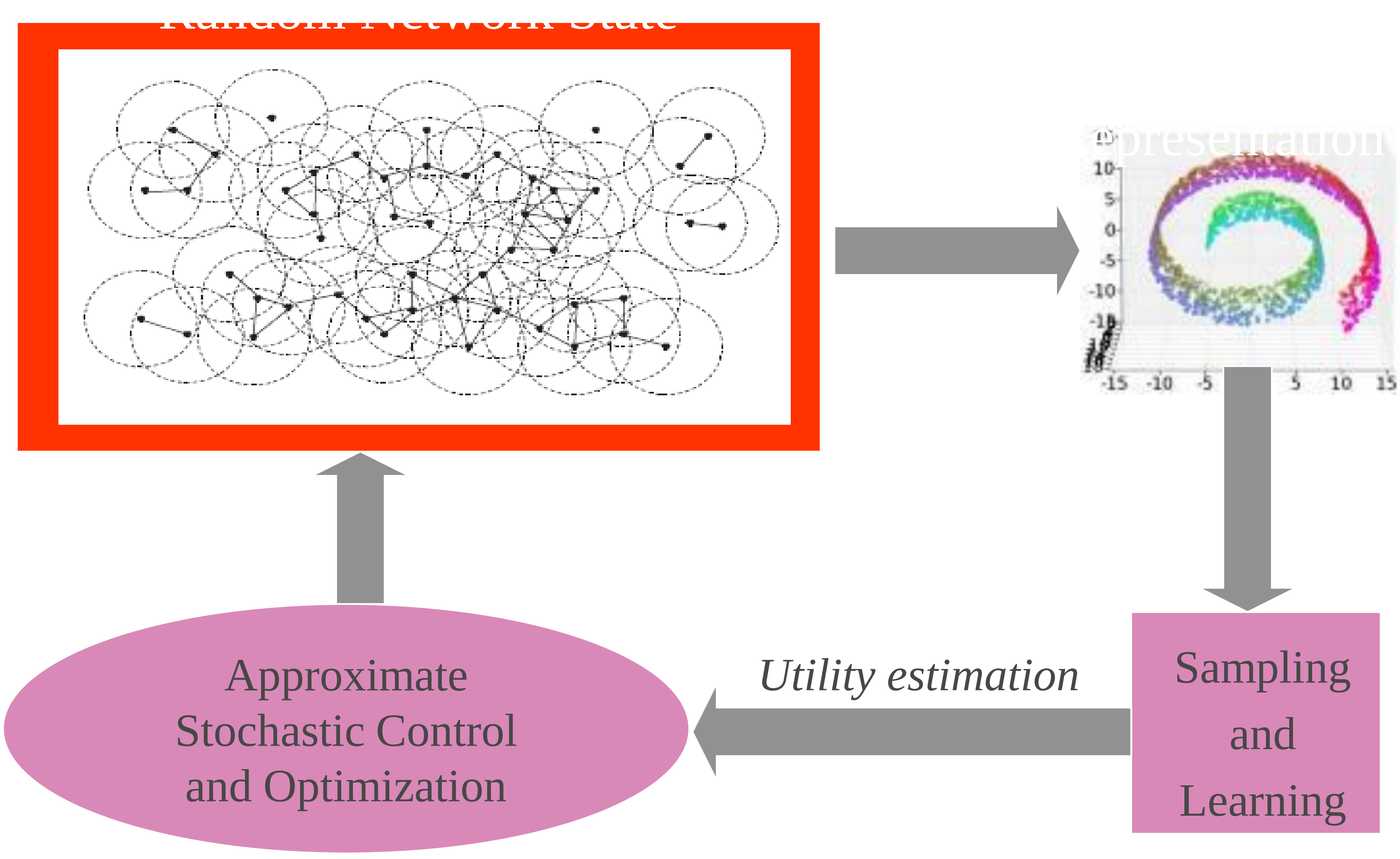


equals

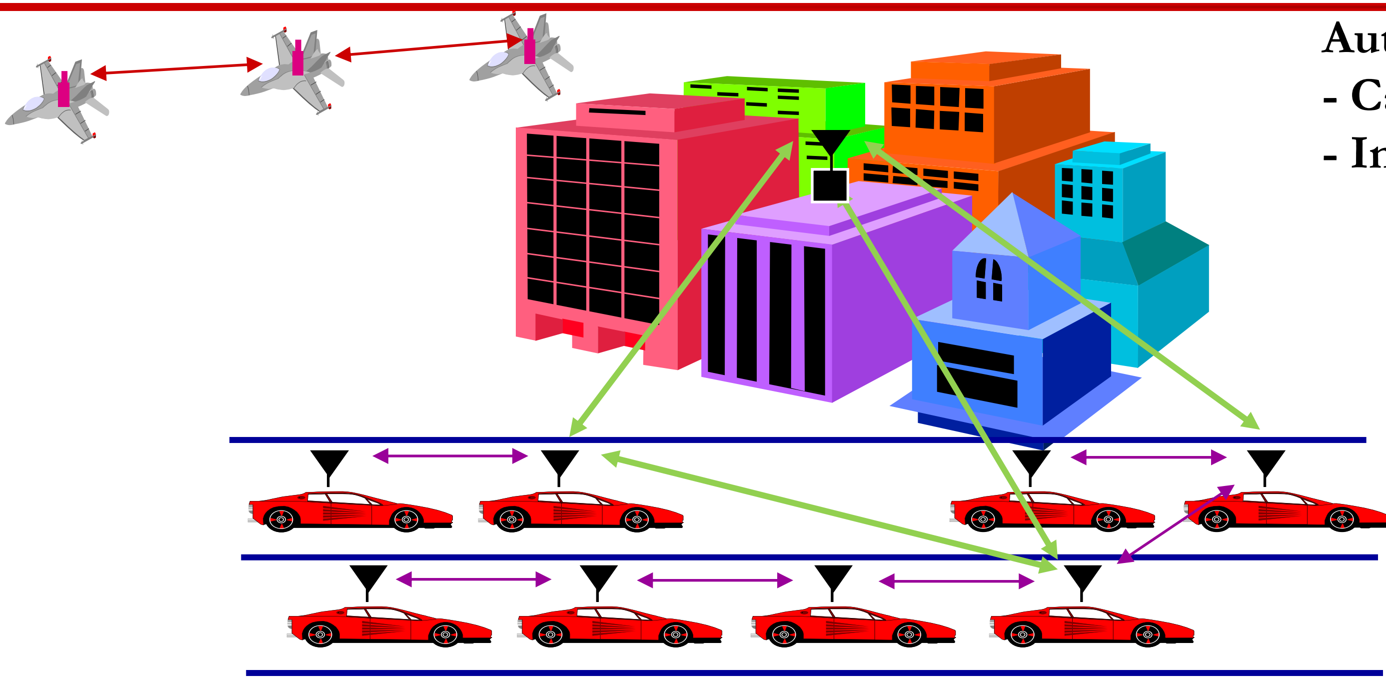


- **Theorem**
  - Optimal among all *time-preserving* nonuniform sampling techniques of rate f_s

Reduced-Dimension Network Design



Communication and Control

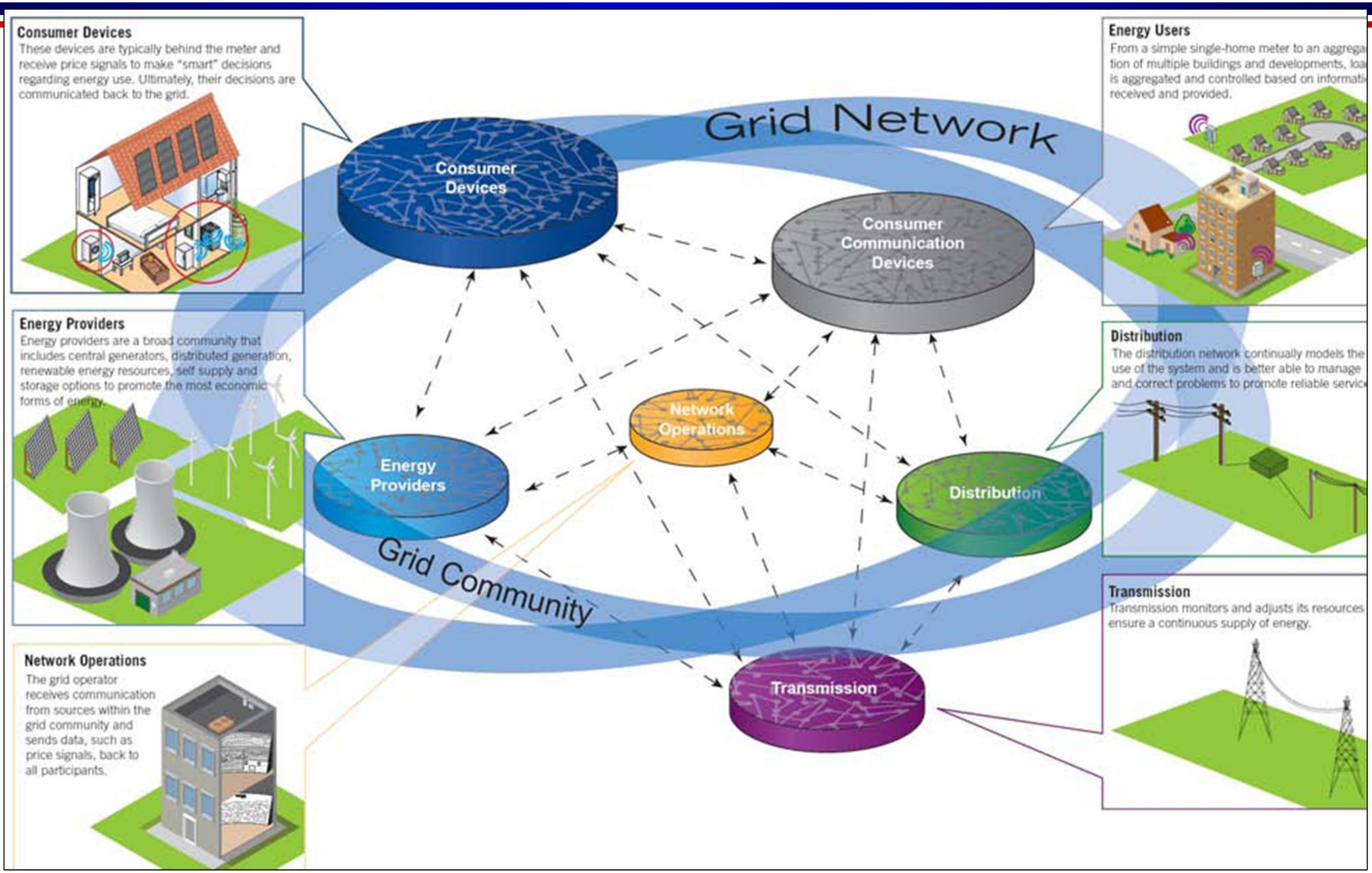


Automated Vehicles
- Cars/planes/UAVs
- Insect flyers

Interdisciplinary design approach

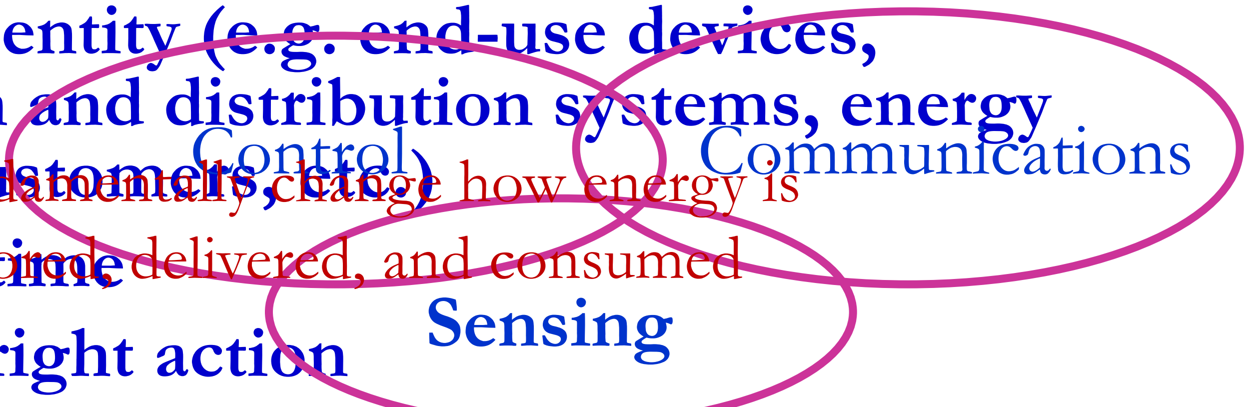
- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss
- Need reliable networks and robust controllers
- Mostly open problems *: Many design challenges*

Smart Grids

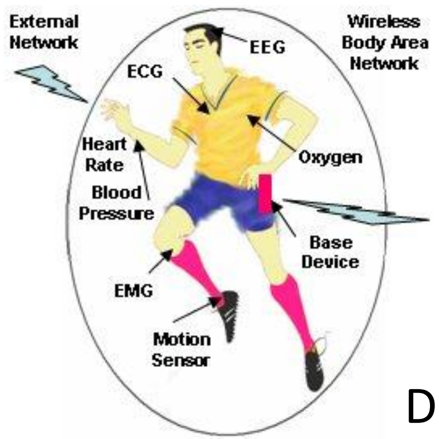

Consumer Devices
These devices are typically behind the meter and receive price signals to make "smart" decisions regarding energy use. Ultimately, their decisions are communicated back to the grid.
Energy Providers
Energy providers are a broad community that includes central generators, distributed generation, renewable energy resources, self supply and storage options to promote the most economic forms of energy.
Network Operations
The grid operator receives communication from sources within the grid community and sends data, such as price signals, back to all participants.
Energy Users
Distribution
The distribution network continually models the use of the system and is better able to manage and correct problems to promote reliable servic
Transmission
Grid Network
Grid Community
Consumer Devices
Consumer Communication Devices
Network Operations
Energy Providers
Distribution
Transmission

The Smart Grid Design Challenge

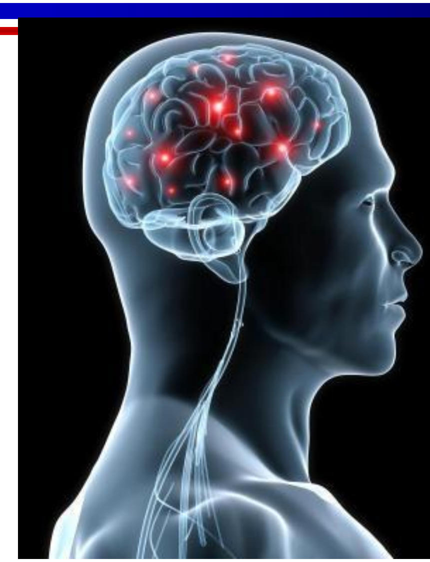
- Design a unified communications and control system overlay
- On top of the existing/emerging power infrastructure
  - To provide the right information
  - To the right entity (e.g. end-use devices, transmission and distribution systems, energy providers, customers, etc.)
  - At the right time
  - To take the right action



Wireless and Health, Biomedicine and Neuroscience

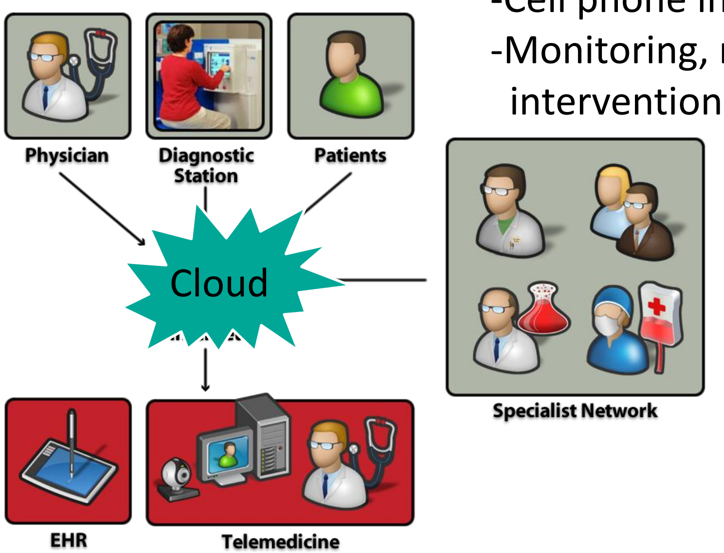


Body-Area Networks



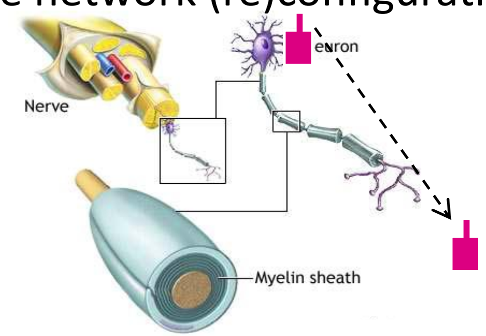
Doctor-on-a-chip

- -Cell phone info repository
- -Monitoring, remote intervention and services



The brain as a wireless network

- - EKG signal reception/modeling
- - Signal encoding and decoding
- - Nerve network (re)configuration



Summary

- Wireless networking is an important research area with many interesting and challenging problems
- Many of the research problems span multiple layers of the protocol stack: little to be gained at just the link layer.
- Cross-layer design techniques are in their infancy: require a new design framework and new analysis tools.
- Hard delay and energy constraints change fundamental design principles of the network.