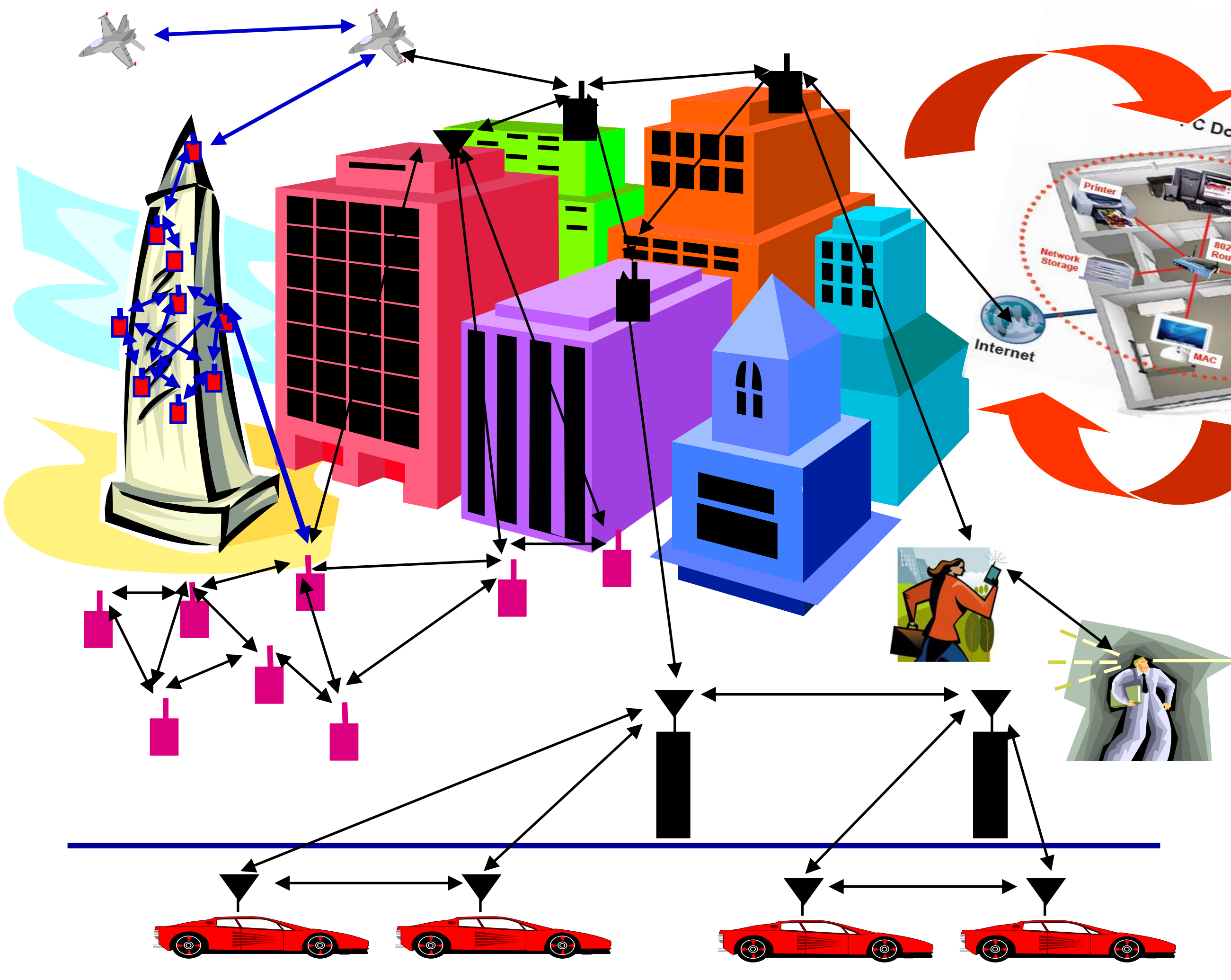
Future Wireless Networks

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 …

Course Information*
People

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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

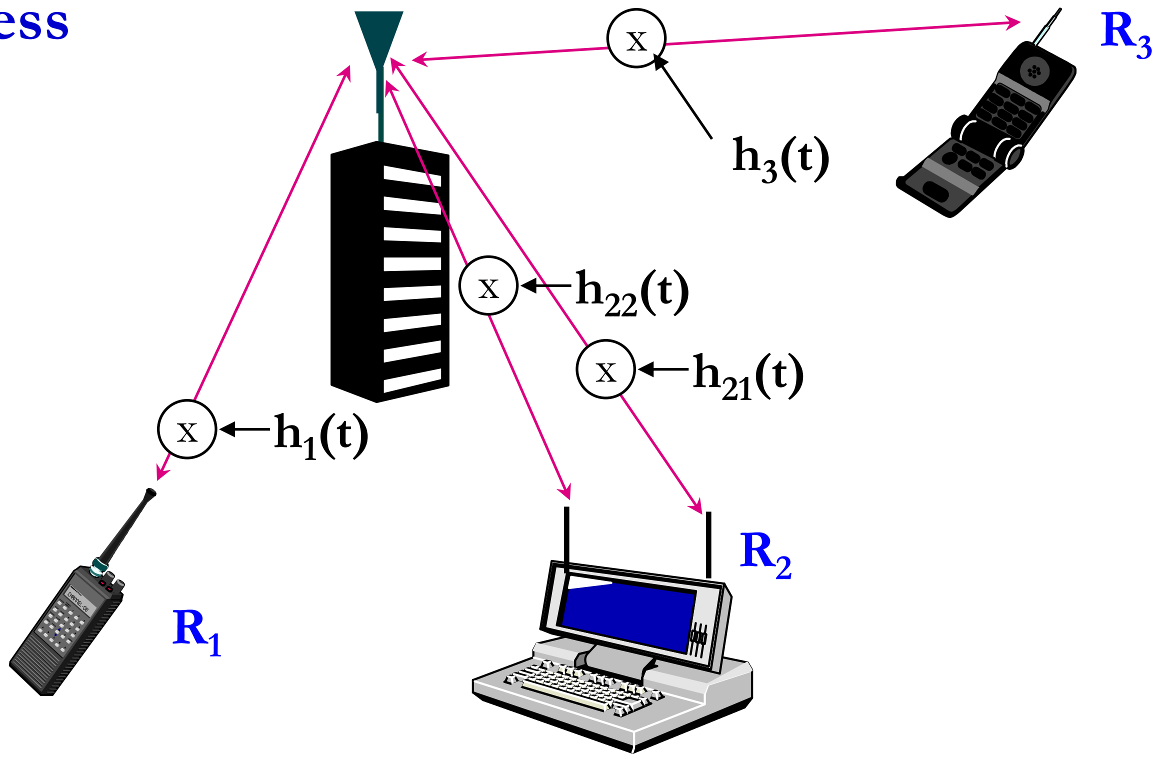
Wireless Network Design Issues

- Multiuser Communications
- Multiple and Random Access
- Cellular System Design
- Ad-Hoc Network Design
- Network Layer Issues
- Cross-Layer Design
- Meeting Application Requirements

Multiuser Channels: Uplink and Downlink

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

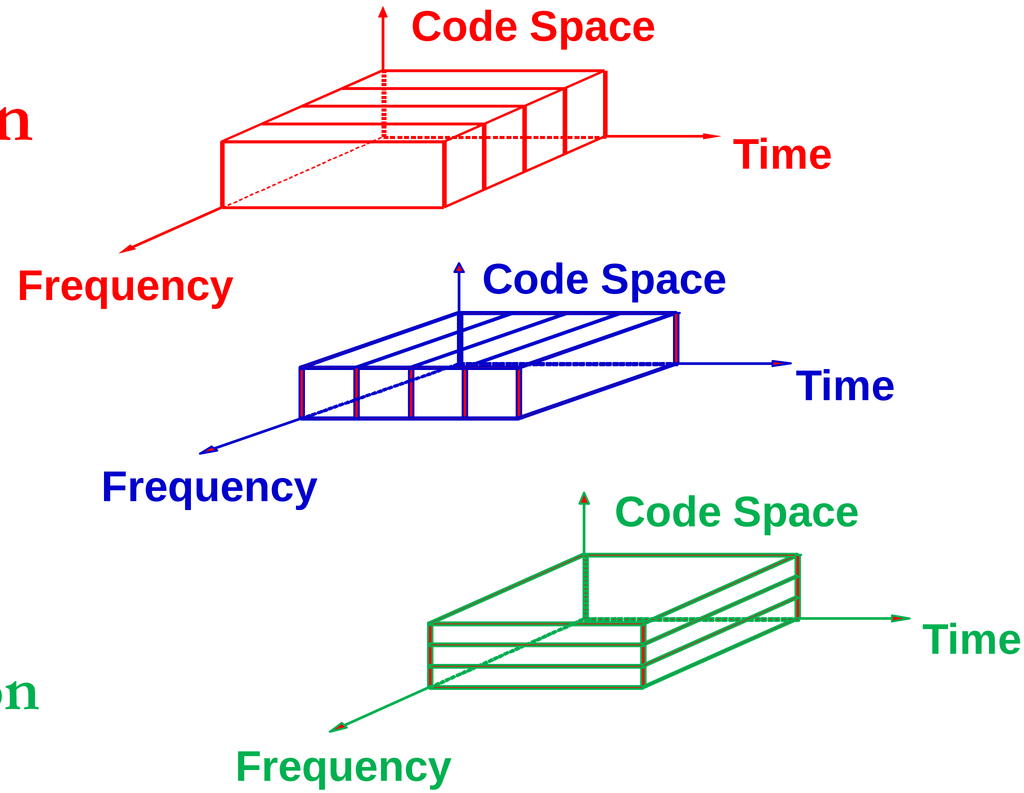
Downlink (Broadcast Channel or BC):
One Transmitter to Many Receivers.



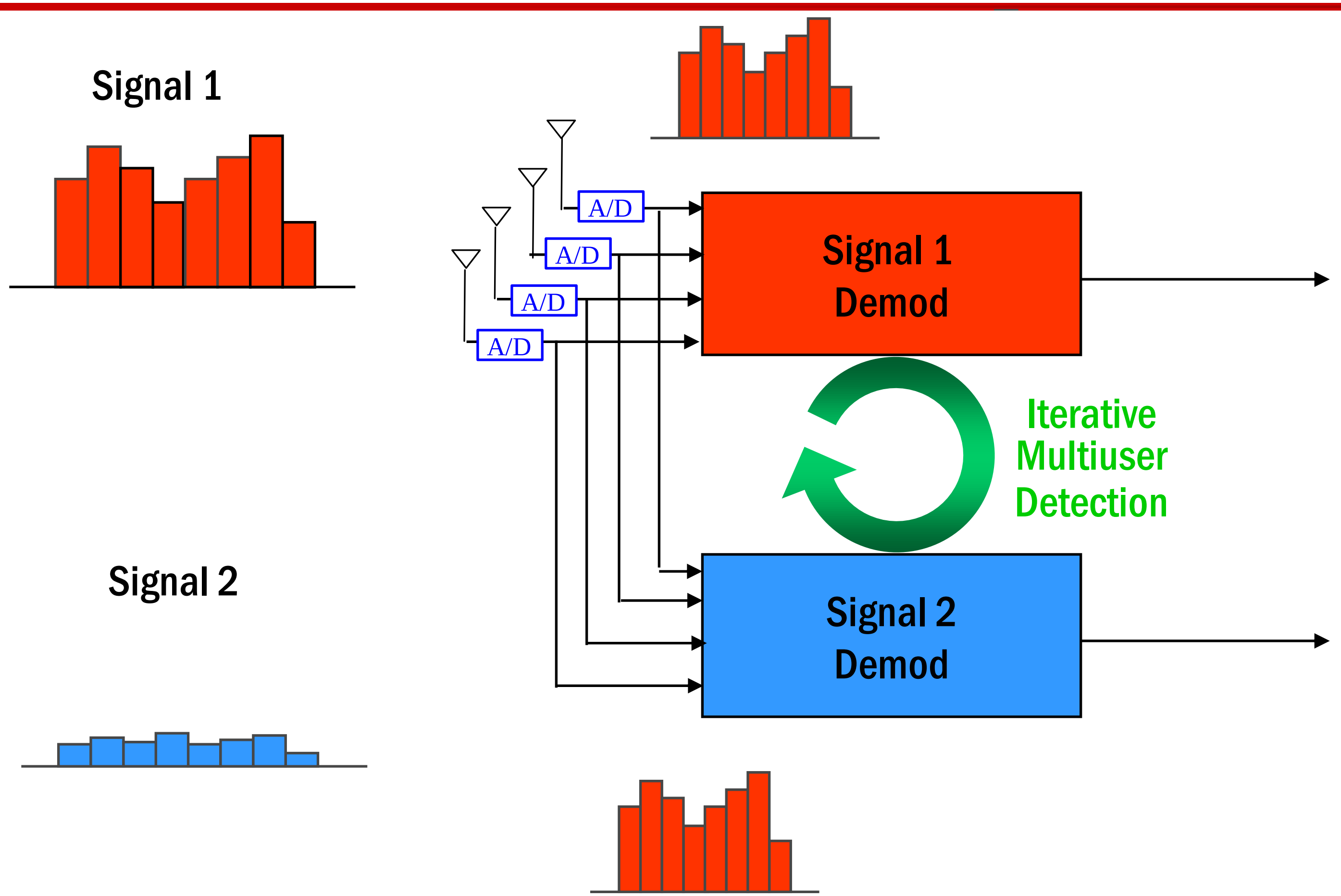
Uplink and Downlink typically duplexed in time or frequency

Bandwidth Sharing

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



Ideal Multiuser Detection

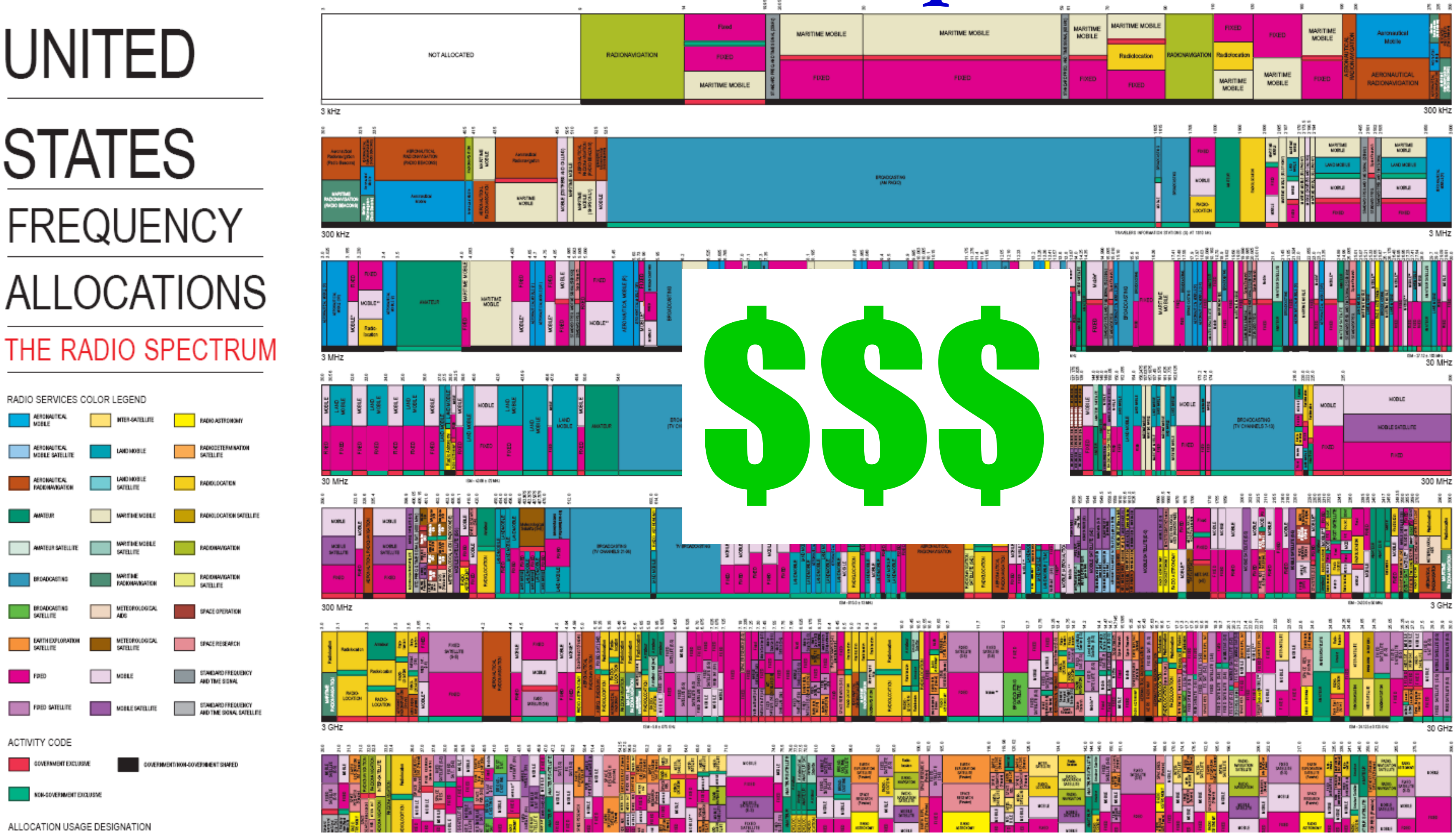


Why Not Ubiquitous Today? Power and A/D Precision

Random Access

- Dedicated channels wasteful for data
  - use statistical multiplexing
- Techniques
  - Aloha
  - Carrier sensing
    - Collision detection or avoidance
  - Reservation protocols
  - PRMA
- Retransmissions used for corrupted data
- Poor throughput and delay characteristics under heavy loading
  - Hybrid methods

Scarce Wireless Spectrum



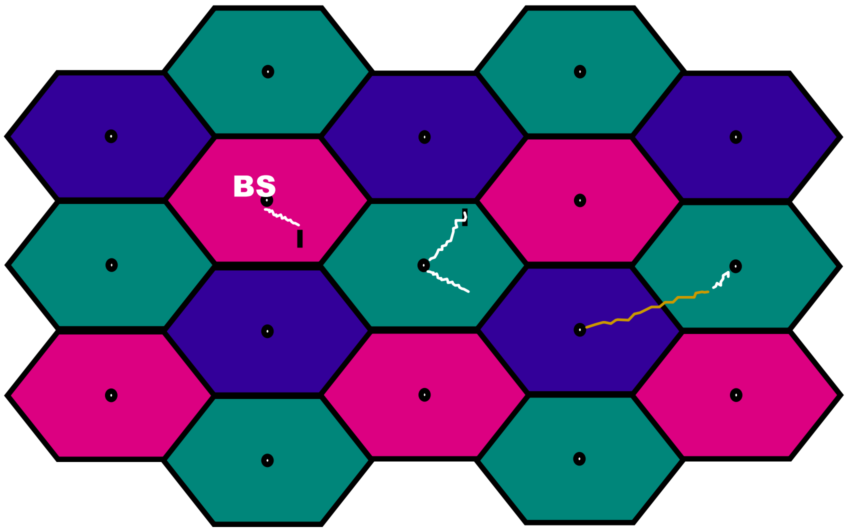
$$$

and Expensive

Spectral Reuse

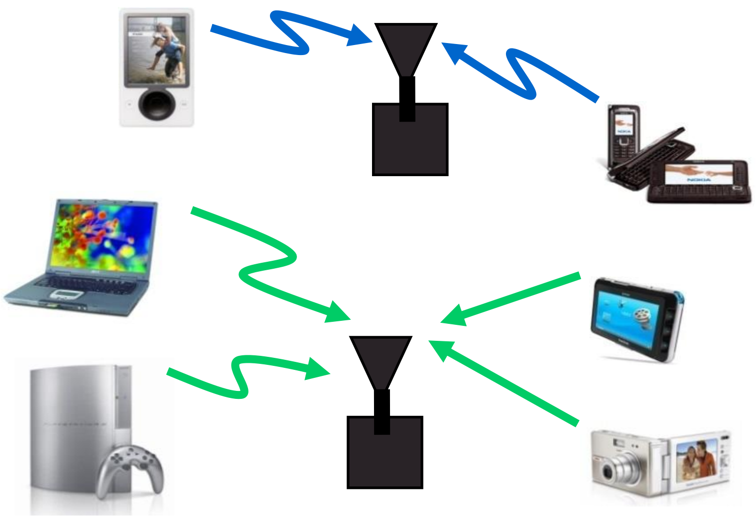
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular, Wimax

and unlicensed bands



Wifi, BT, UWB,…

Reuse introduces interference

Interference: *Friend or Foe?*

- **If treated as noise: Foe**

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

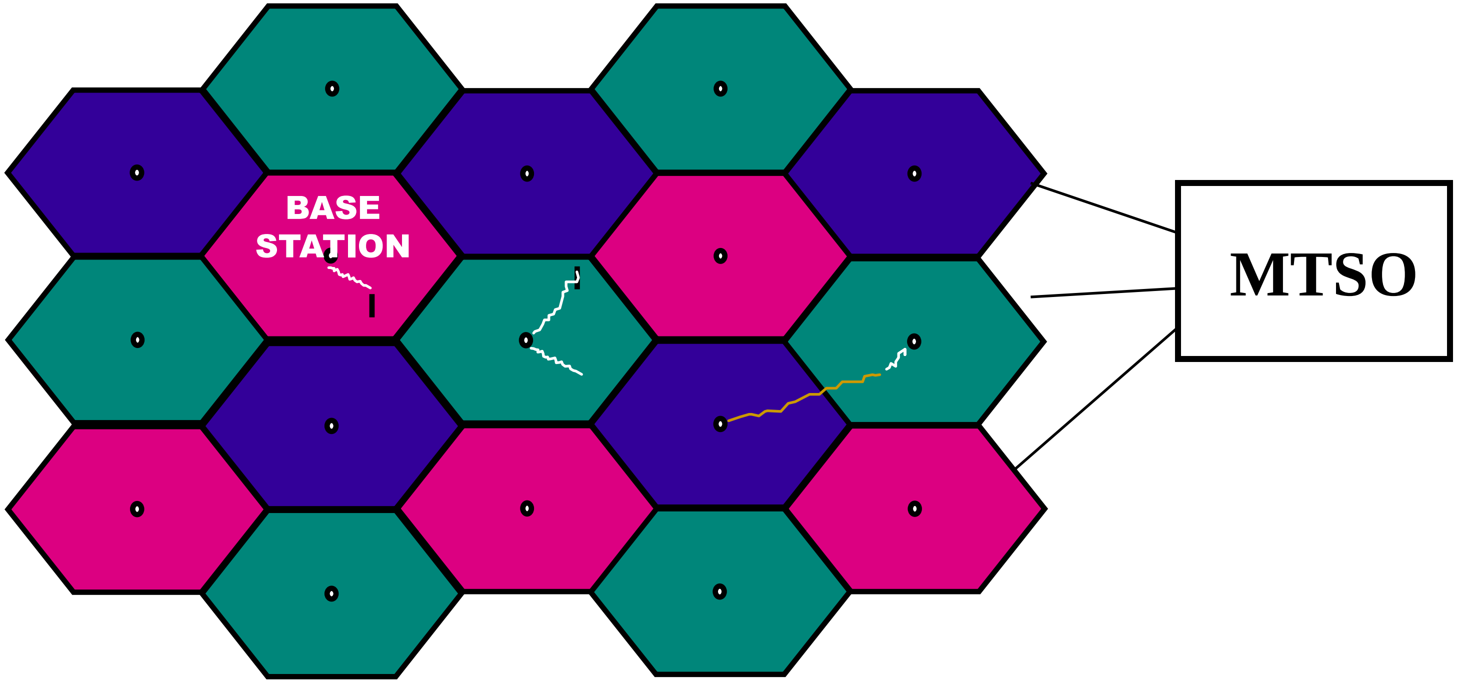
Increases BER
Reduces capacity

- **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

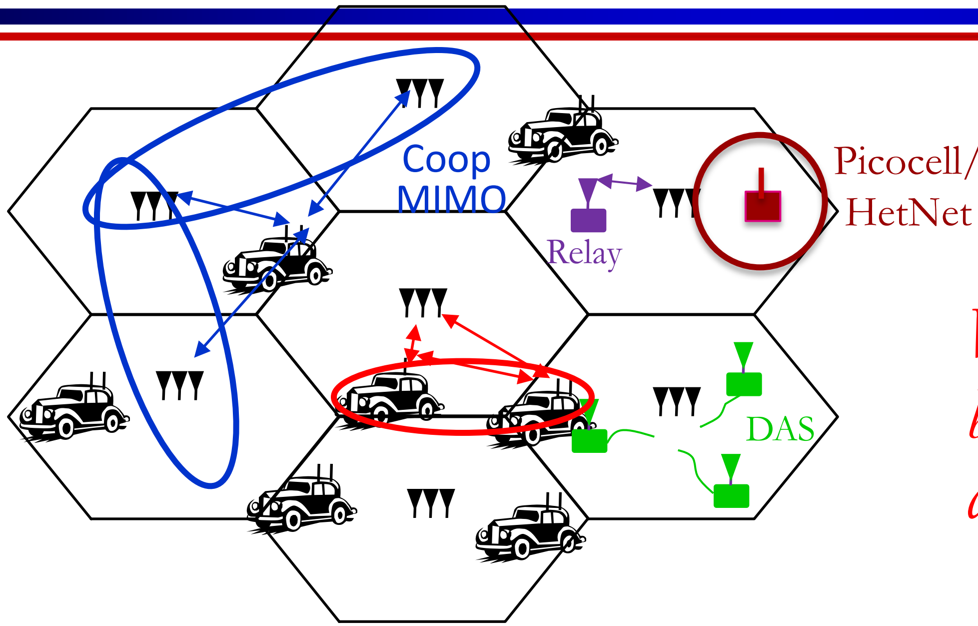
- 1G: Analog systems, large frequency reuse, large cells, uniform standard
- 2G: Digital systems, less reuse (1 for CDMA), smaller cells, multiple standards, evolved to support voice and data (IS-54, IS-95, GSM)
- 3G: Digital systems, WCDMA competing with GSM evolution.
- 4G: OFDM/MIMO



MIMO in Cellular: *Performance Benefits*

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

Rethinking "Cells" in Cellular

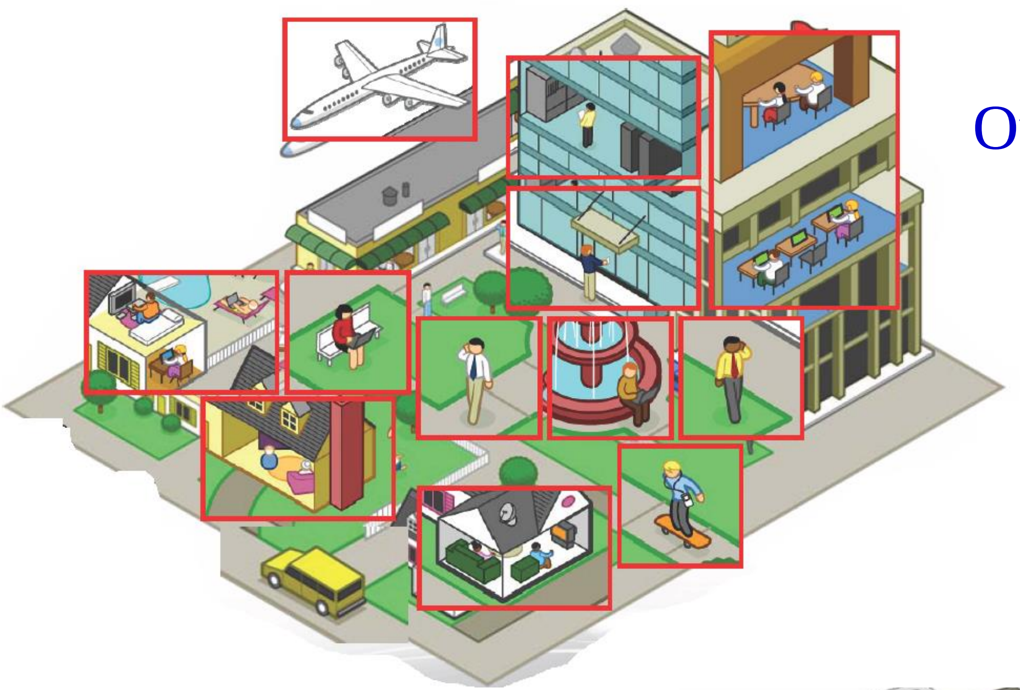


How should cellular systems be designed?

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.**

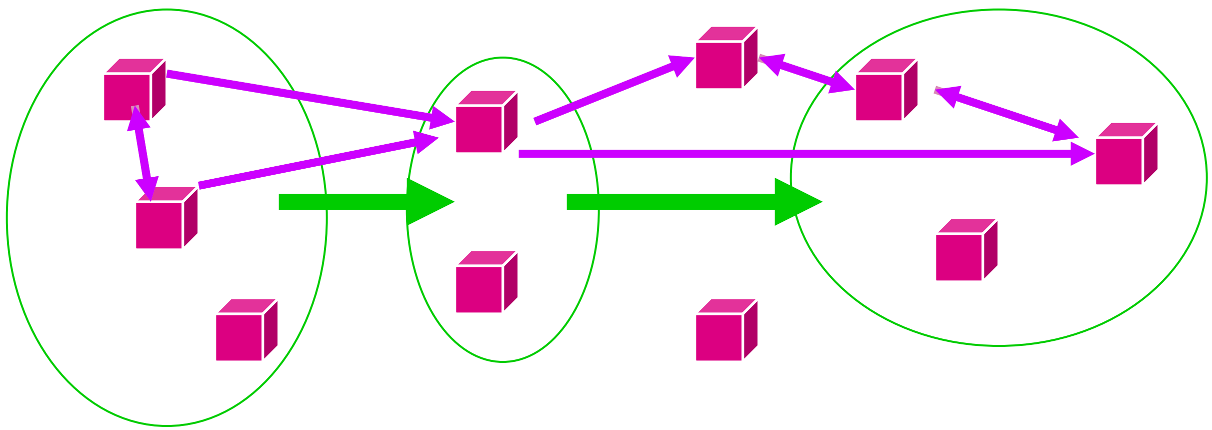
Ad-Hoc/Mesh Networks



Outdoor Mesh

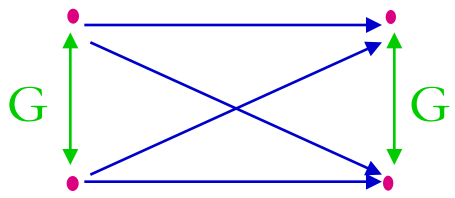
Indoor Mesh

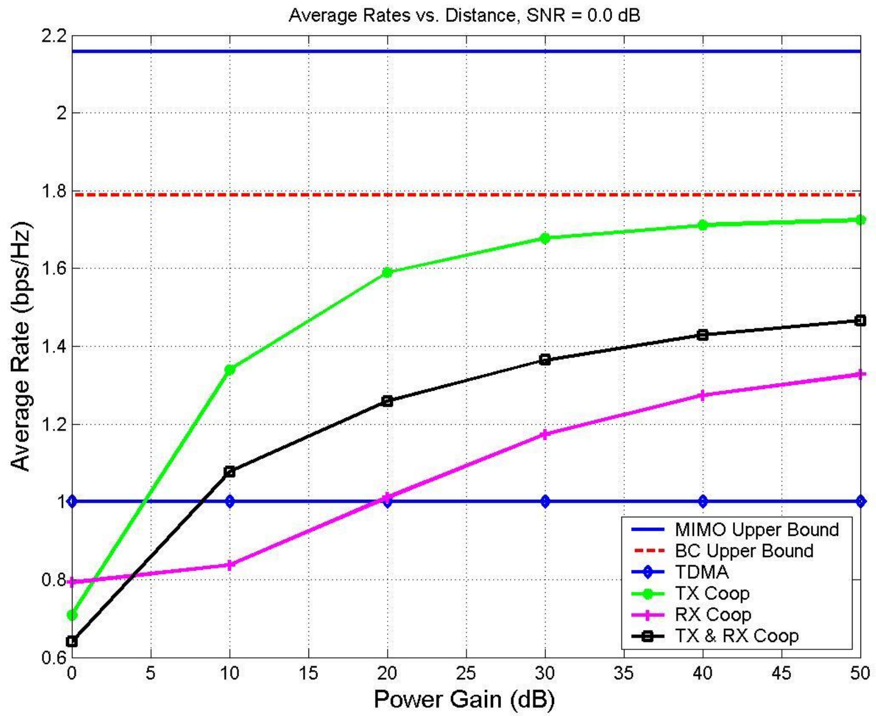
Cooperation in Ad-Hoc Networks



- Similar to mobile cooperation in cellular:
  - Virtual MIMO , generalized relaying, interference forwarding, and one-shot/iterative conferencing
- Many theoretical and practice issues:
  - Overhead, half-duplex, grouping, dynamics, synch, …

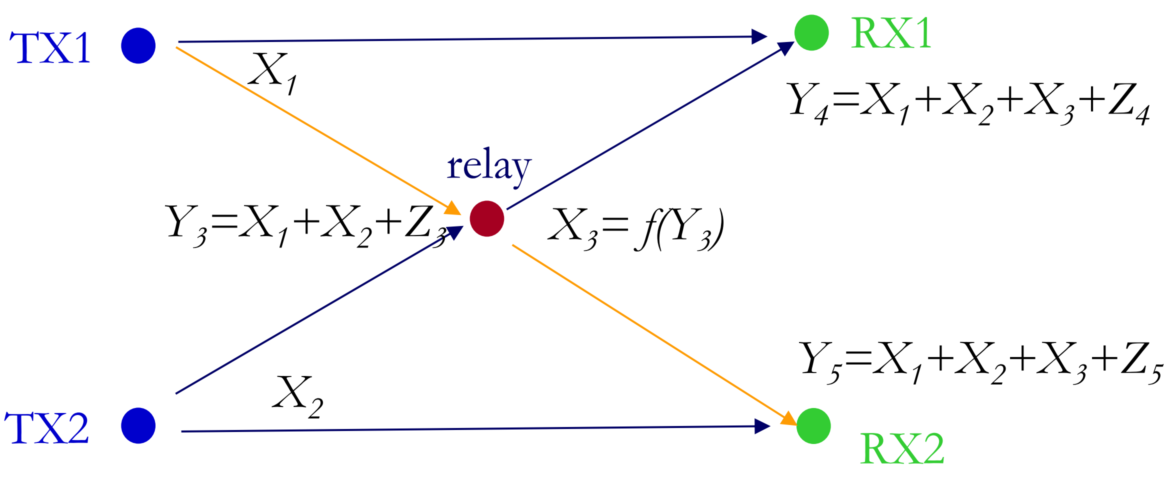
Capacity Gain with Virtual MIMO (2x2)





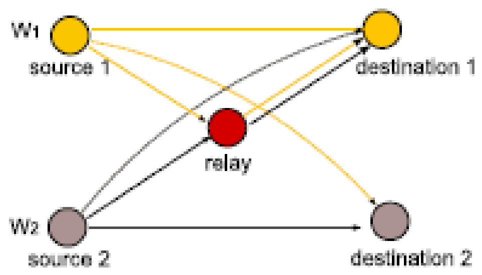
- TX cooperation needs high-capacity wired or wireless cooperative link to approach broadcast channel bound
- Gains on order of 2x in theory, what about in practice?
- How many nodes should cooperate, and with whom?

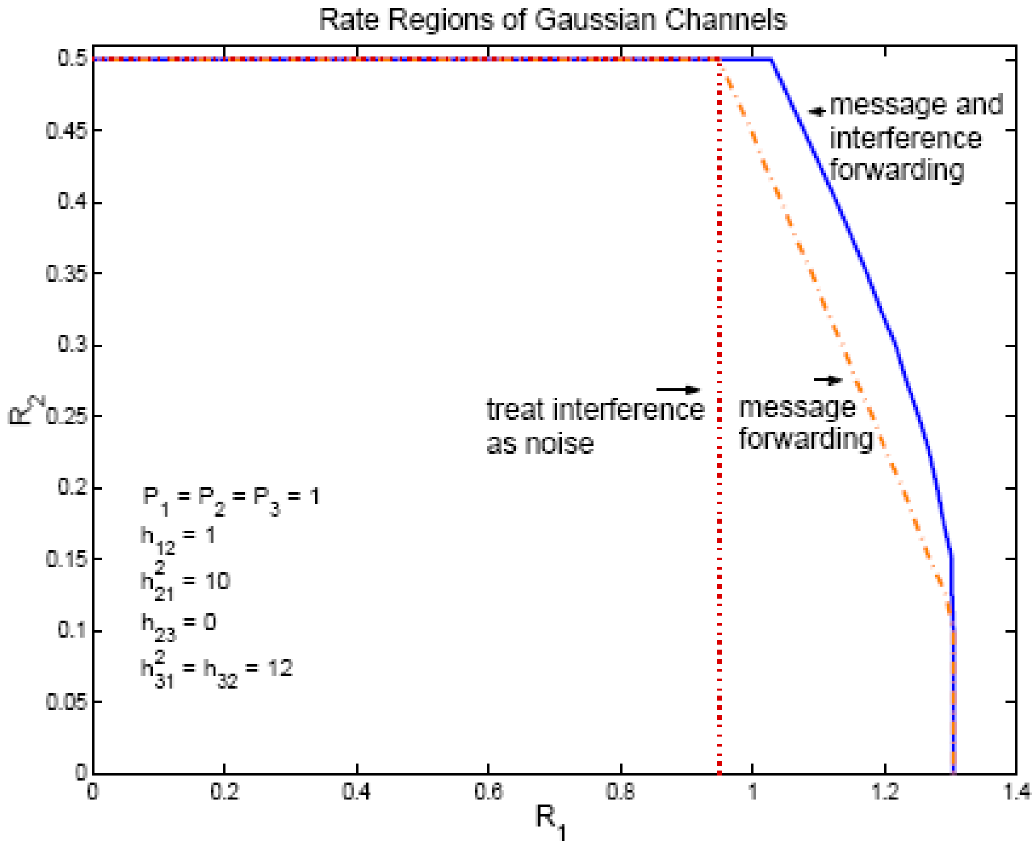
Generalized Relaying



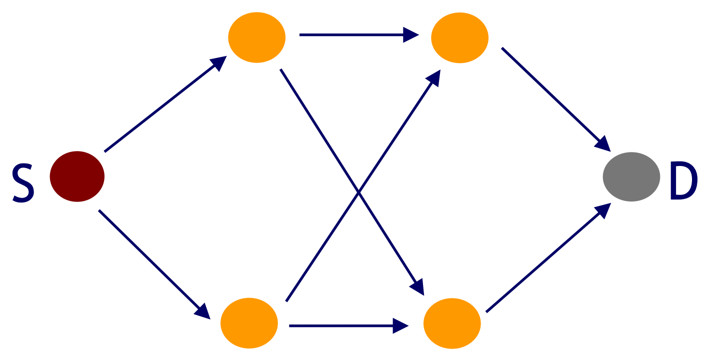
- Can forward message and/or interference
  - **Relay can forward all or part of the messages**
    - **Much room for innovation**
  - **Relay can forward interference**
    - **To help subtract it out**

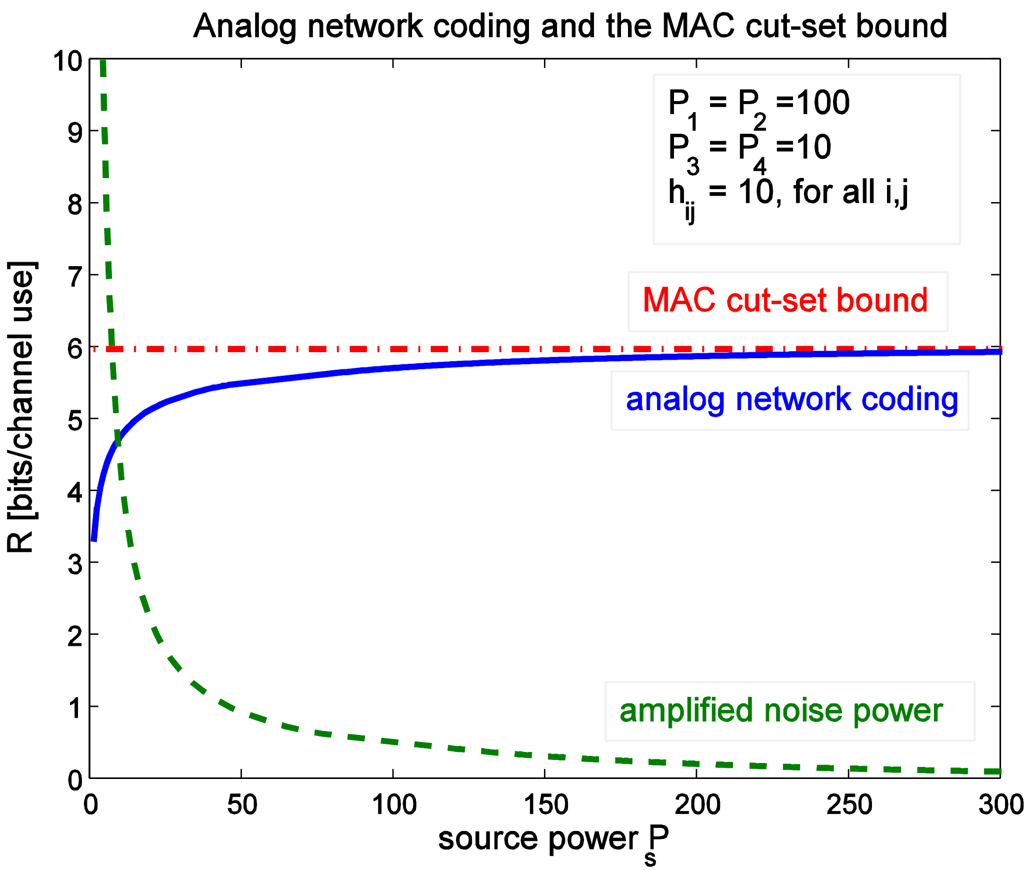
Beneficial to forward both interference and message





In fact, it can achieve capacity





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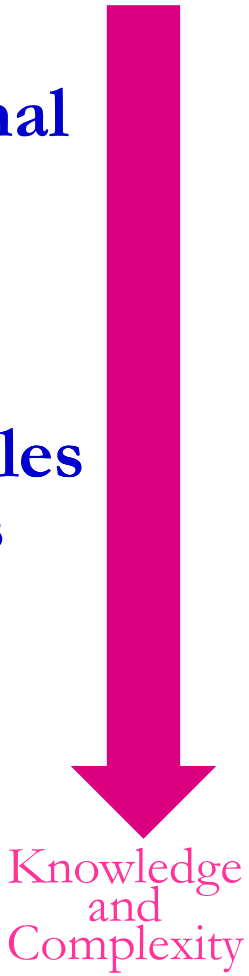
Intelligence beyond Cooperation: *Cognition*

- Cognitive radios can support new wireless users in existing crowded spectrum
  - <u>Without degrading performance of existing users</u>
- 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

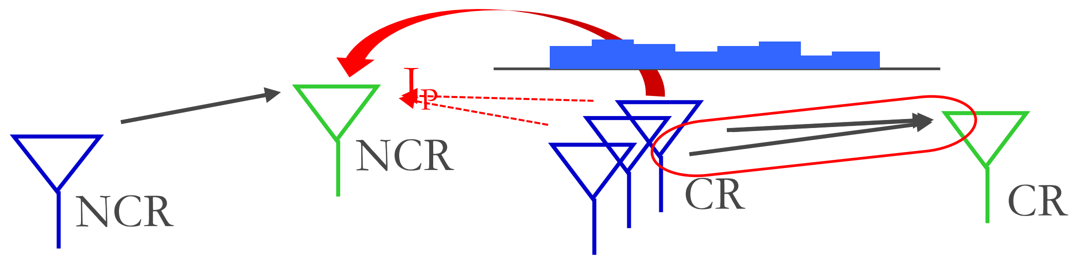
Cognitive Radio Paradigms

- 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



Underlay Systems

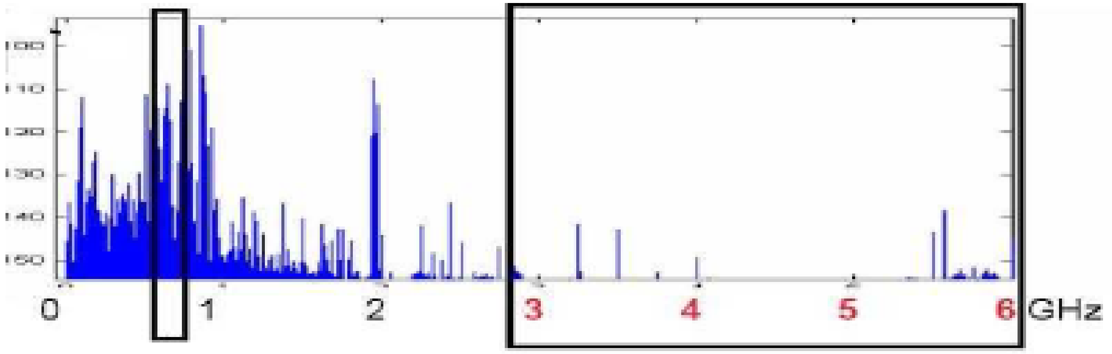
- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold



- 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

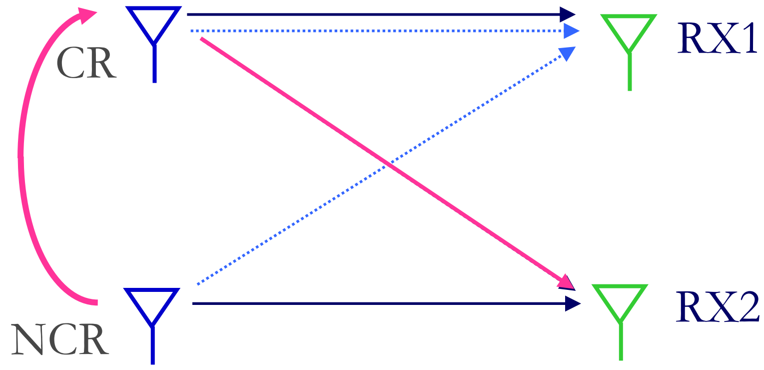
- Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies
  - Original motivation for "cognitive" radios (Mitola'00)



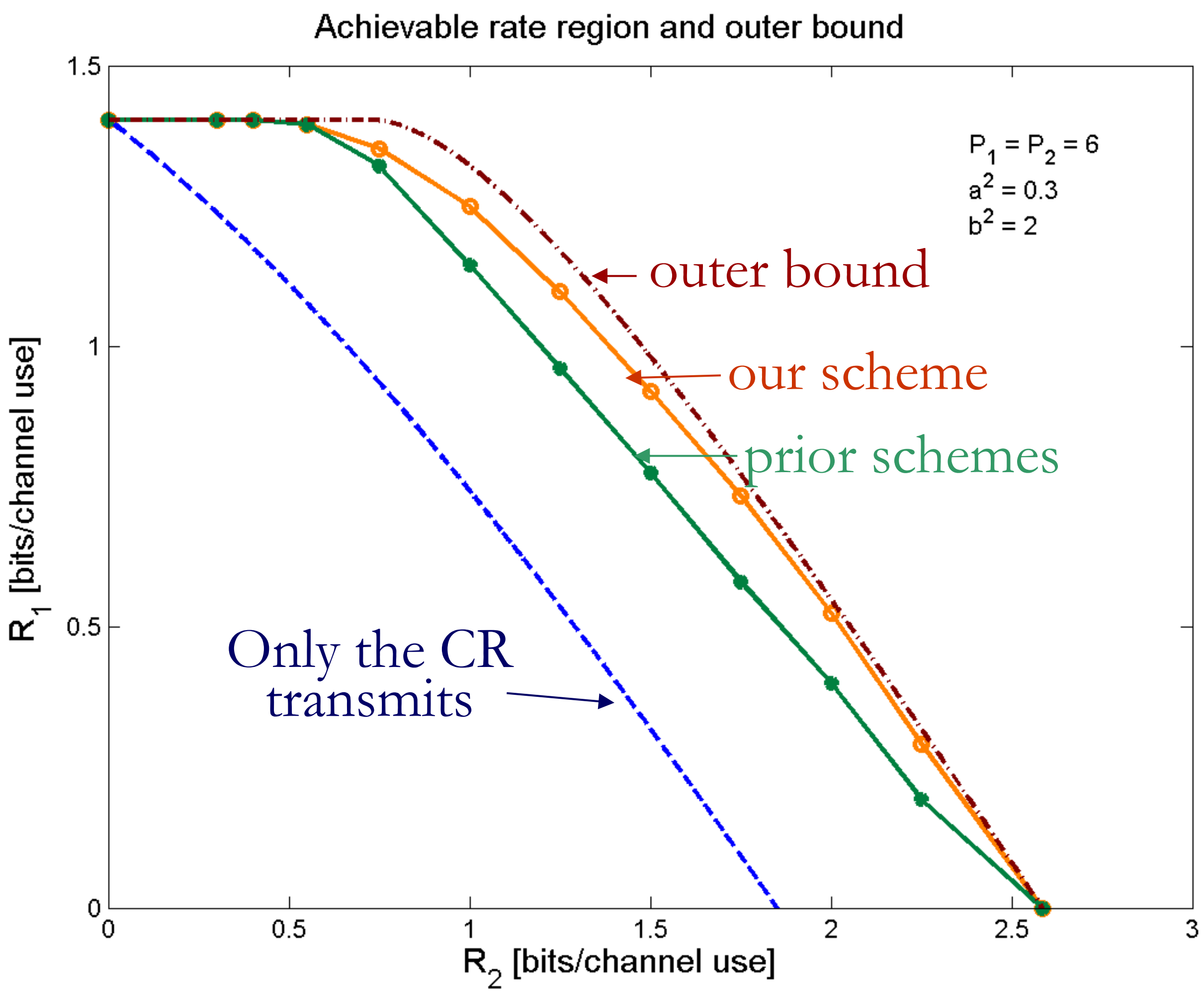
- These holes can be used for communication
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication with minimal interference to noncognitive users

Overlay Systems

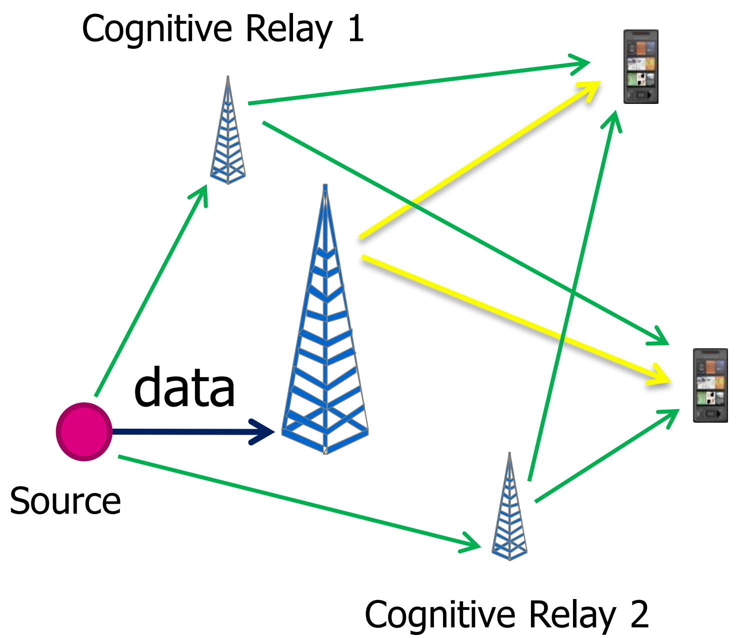
- Cognitive user has knowledge of other user's message and/or encoding strategy
  - Used to help noncognitive transmission
  - Used to presubtract noncognitive interference



Performance Gains from Cognitive Encoding



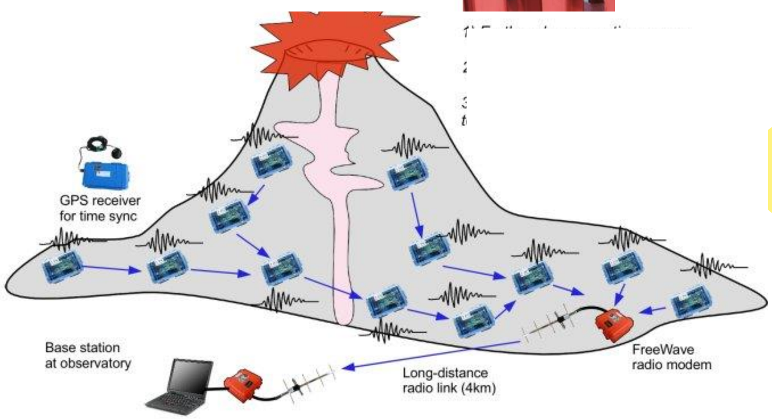
Cellular Systems with Cognitive Relays

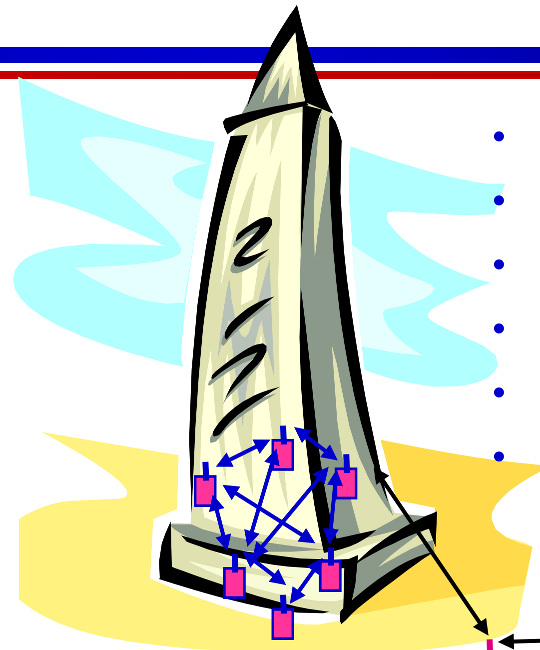


- Enhance robustness and capacity via cognitive relays
  - Cognitive relays overhear the source messages
  - Cognitive relays then cooperate with the transmitter in the transmission of the source messages
  - Can relay the message even if transmitter fails due to congestion, etc.

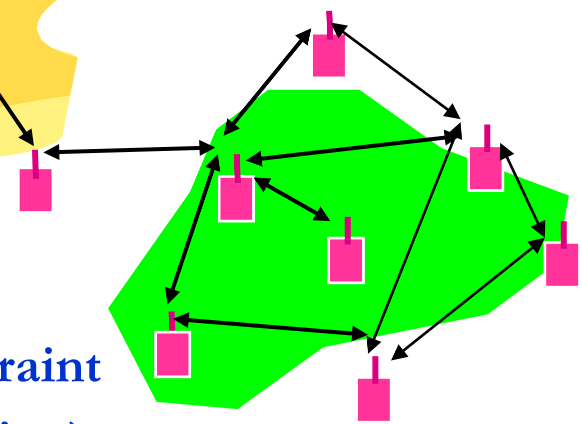
Can extend these ideas to MIMO systems

Wireless Sensor and "Green" Networks





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

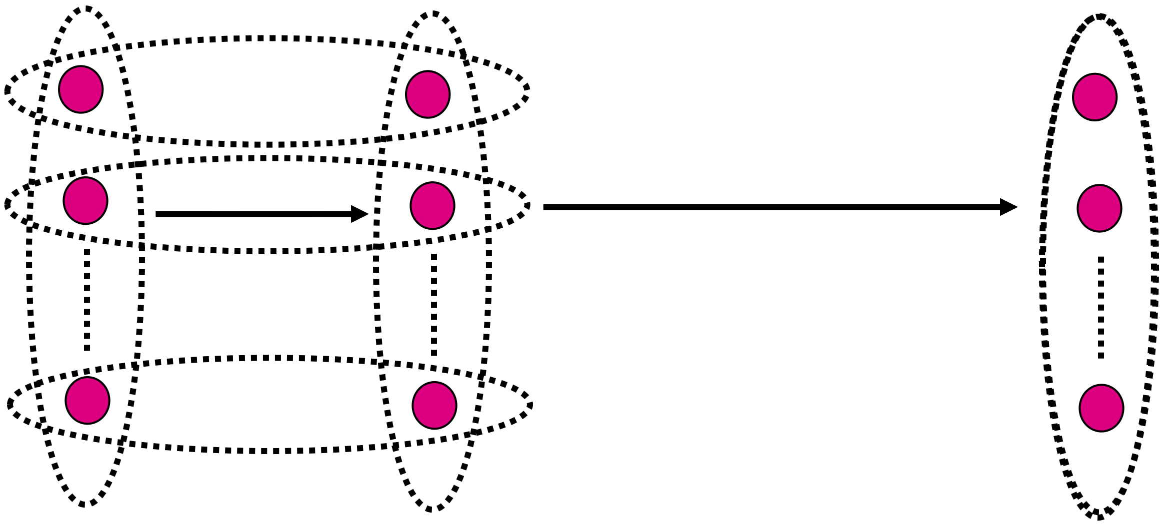


- Energy (transmit and processing) is driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices
- Similar ideas can be used to re-architect systems and networks to be green

Energy-Constrained Nodes

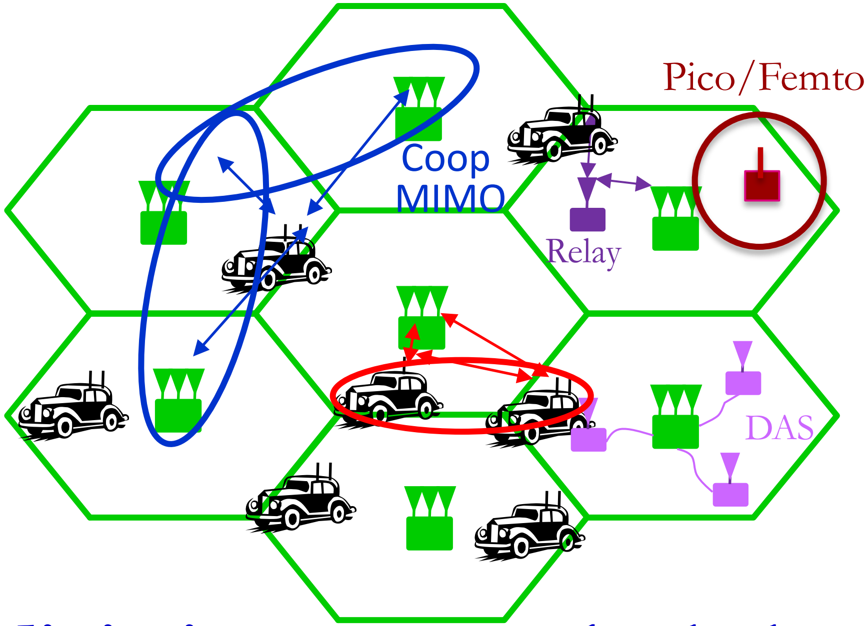
- Each node can only send a <u>finite</u> number of bits.
  - Transmit energy minimized by maximizing bit time
  - Circuit energy consumption increases with bit time
  - Introduces a delay versus energy tradeoff for each bit
- Short-range networks must consider transmit, circuit, and processing energy.
  - 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.

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?

Green" Cellular Networks



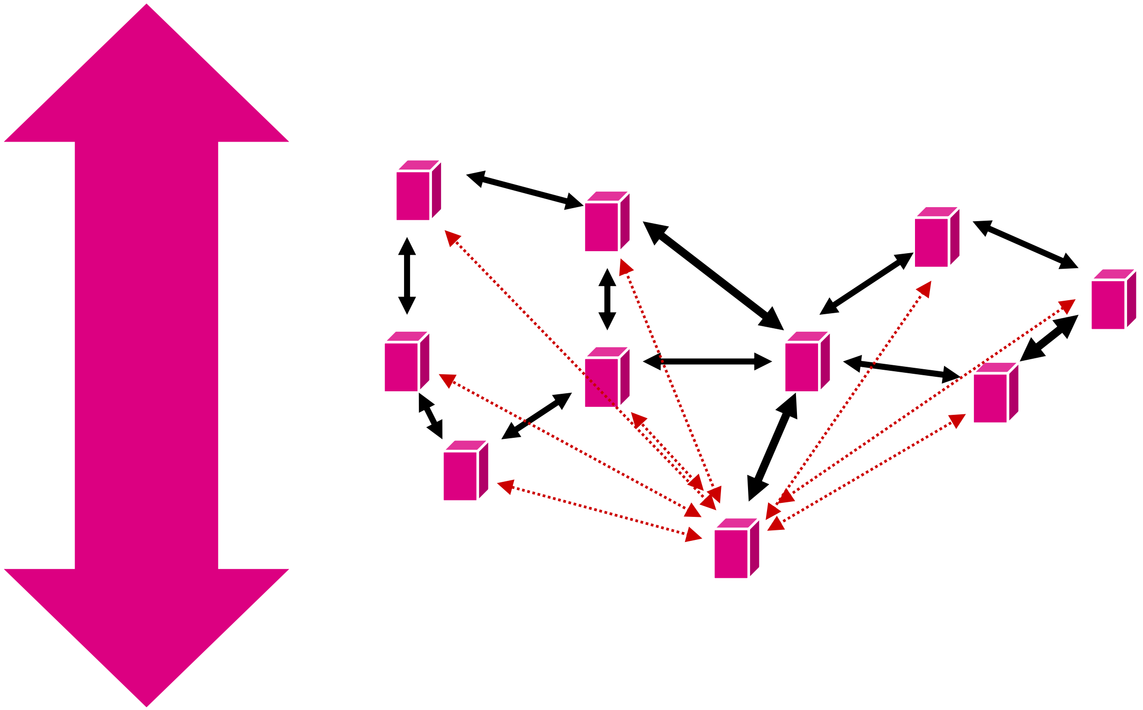
How should cellular systems be redesigned for minimum energy?

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**

Crosslayer Design in Wireless Networks

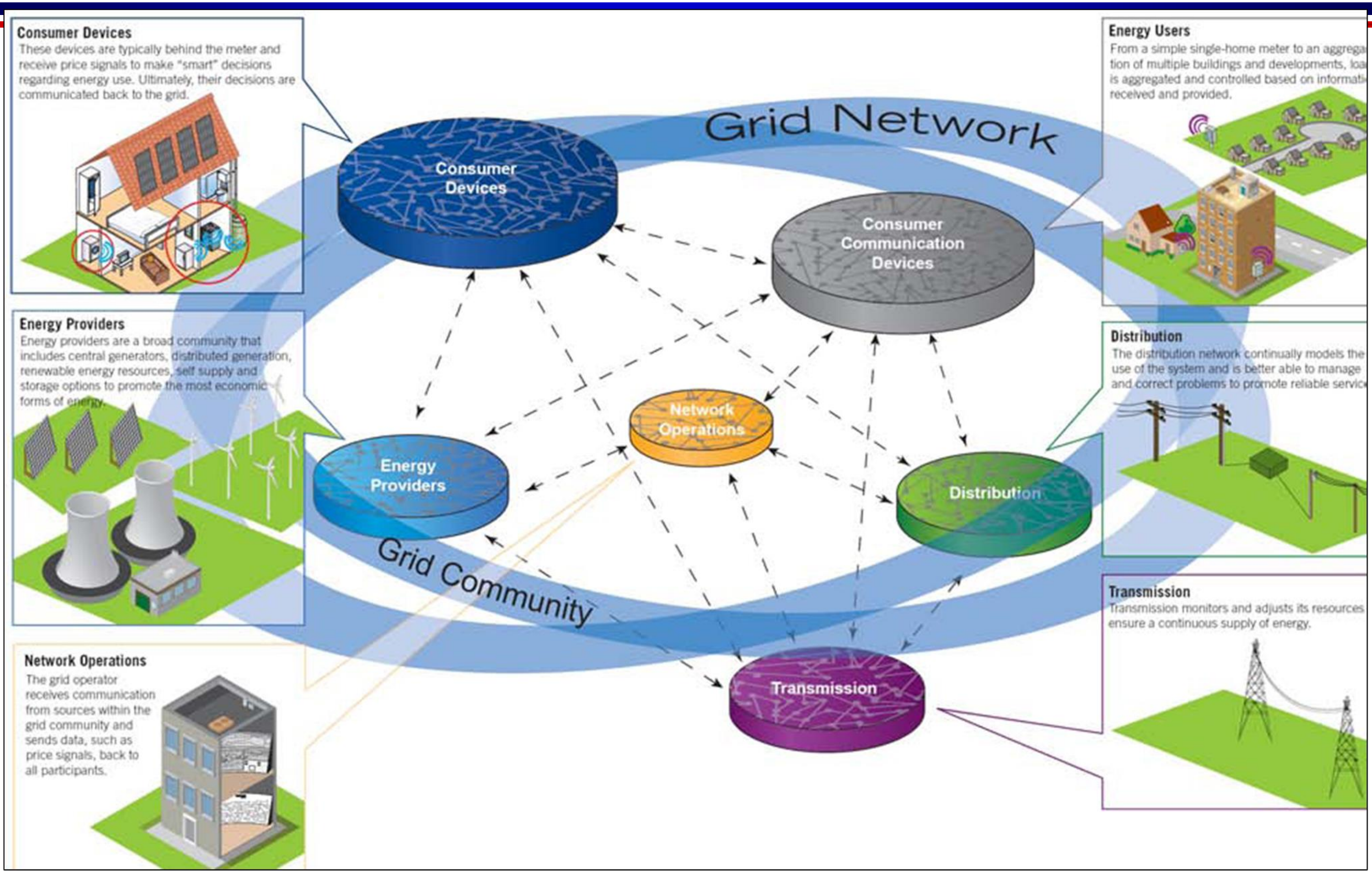
- Application
- Network
- Access
- Link
- Hardware



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

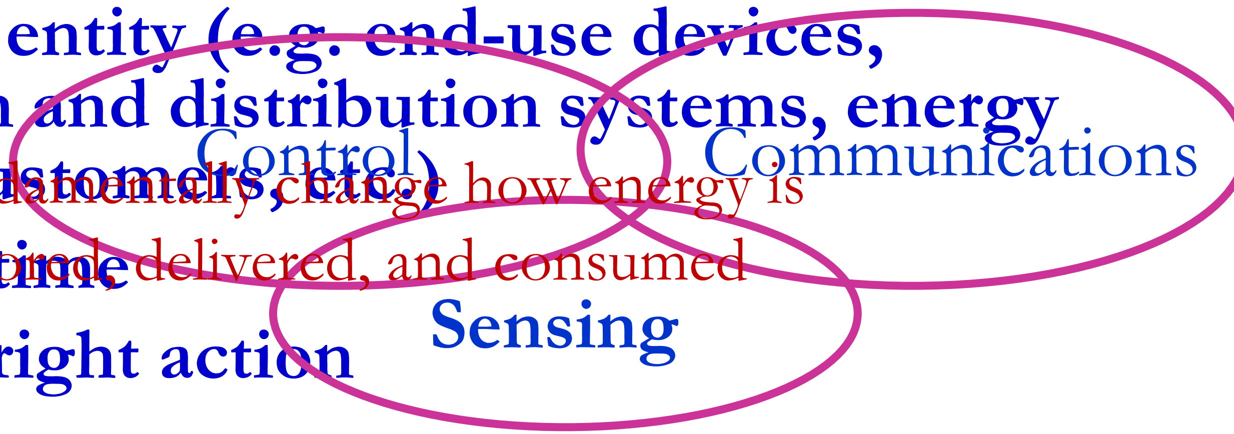
This performance is dictated by the application

Key Application: Smart Grids

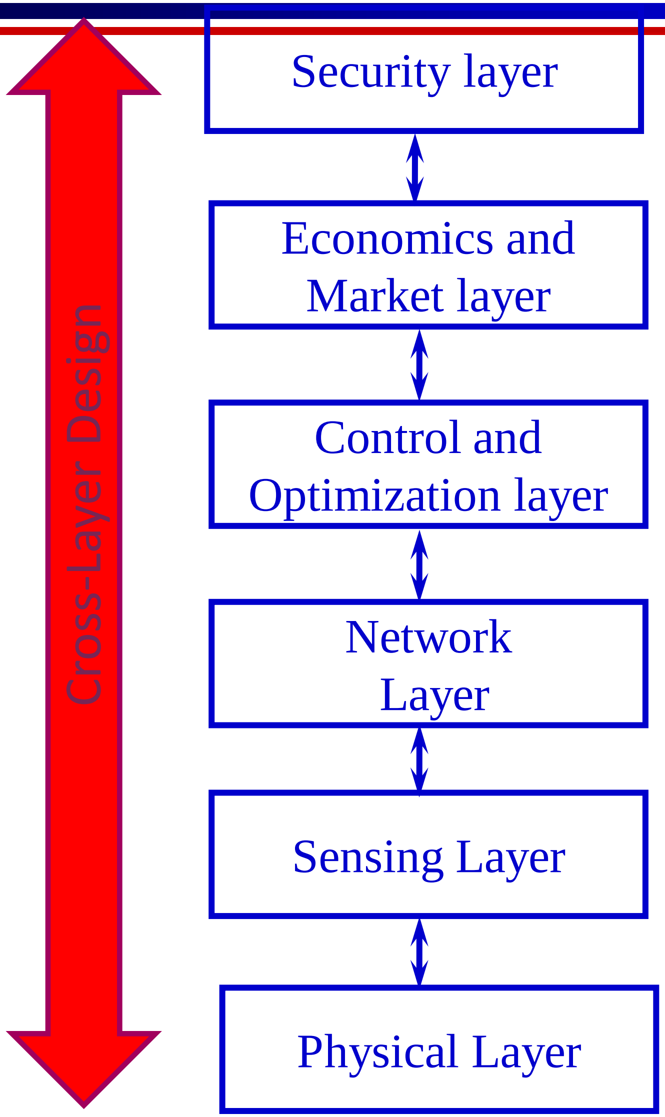


The Smart Grid Design Challenge

- 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



Possible Dichotomy for Smart Grid Design



Encryption, antijam, denial of use, impersonation, cyber-physical security, …

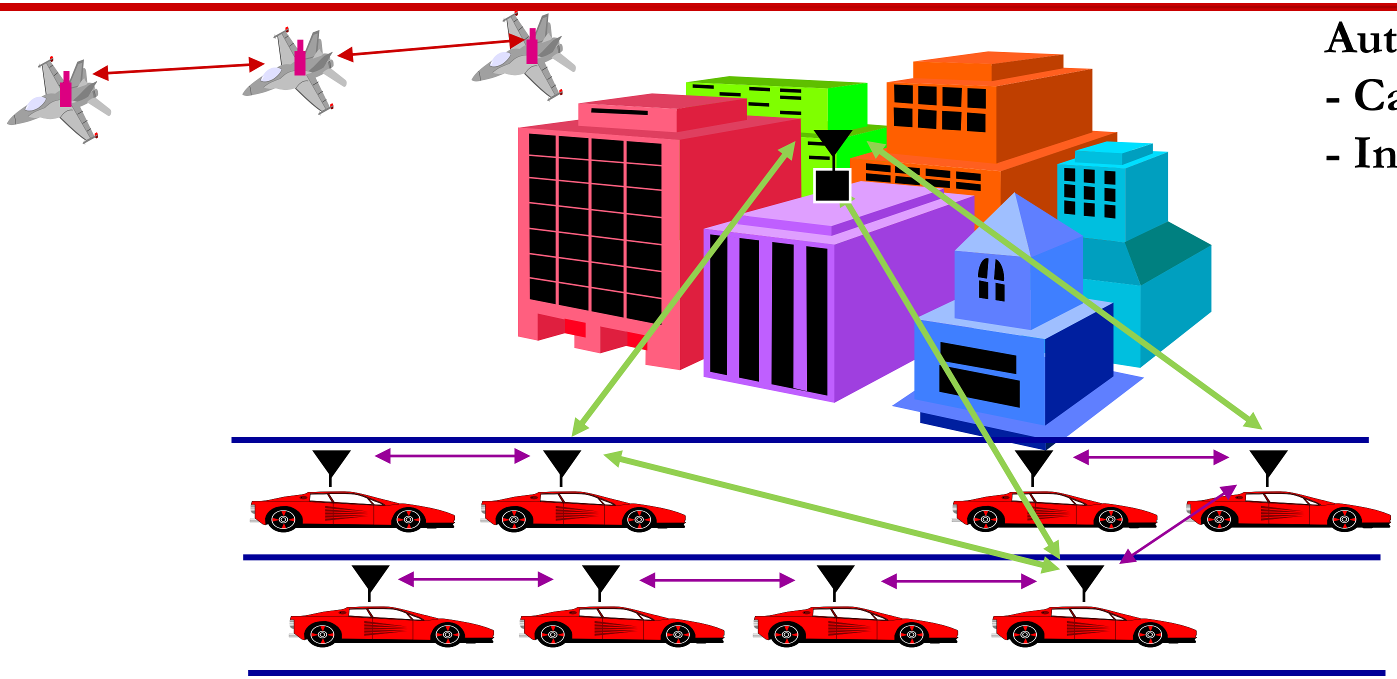
Pricing, incentives, markets, …

Real-time/embedded control, demand-response, resource allocation, fault tolerance, …

Sensor networks, HAN, Wifi, Wimax, Cellular, …

Electric, gas, and water sensors, HVAC, …

Automated Highways

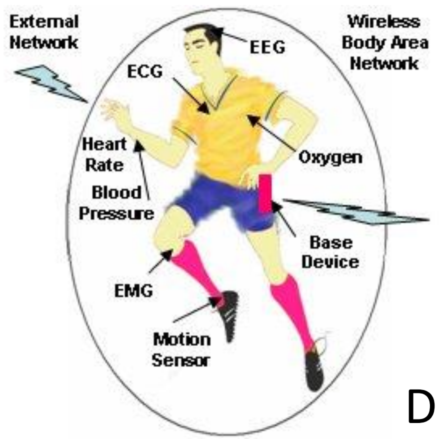


Automated Vehicles
- Cars/planes/UAVs
- Insect flyers

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*

Wireless and Health, Biomedicine and Neuroscience

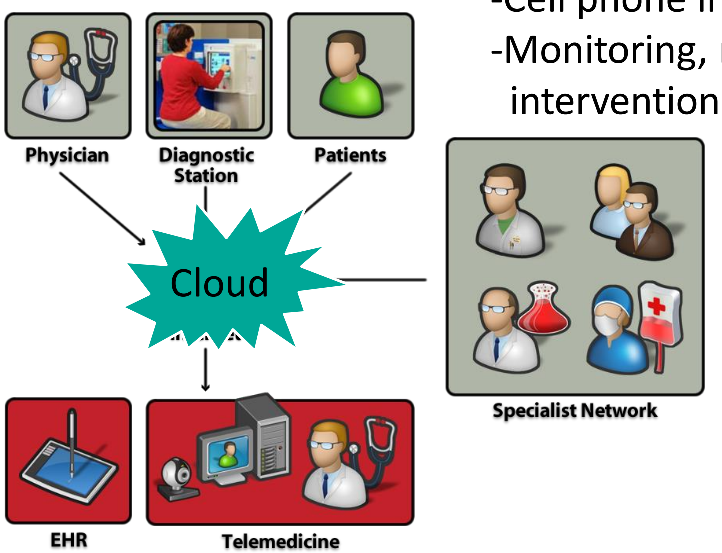


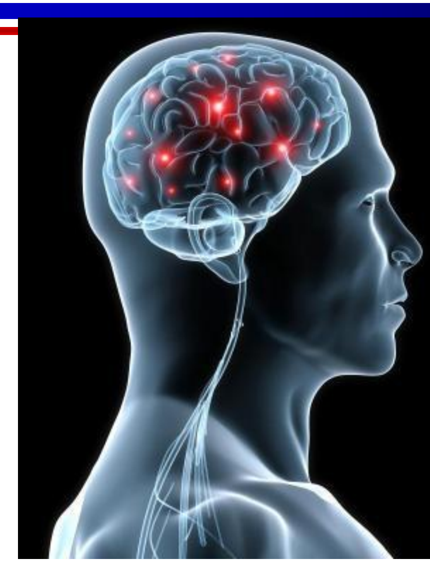
Body-Area Networks

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