The next wave in wireless technology: *Challenges and Solutions*

Andrea Goldsmith

Stanford University

ICCCN
San Francisco, CA
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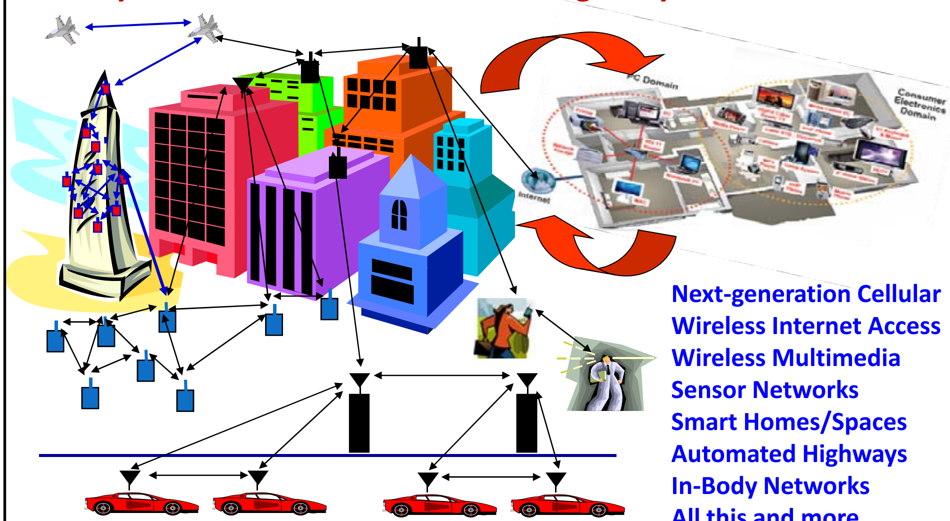
Future Wireless Networks

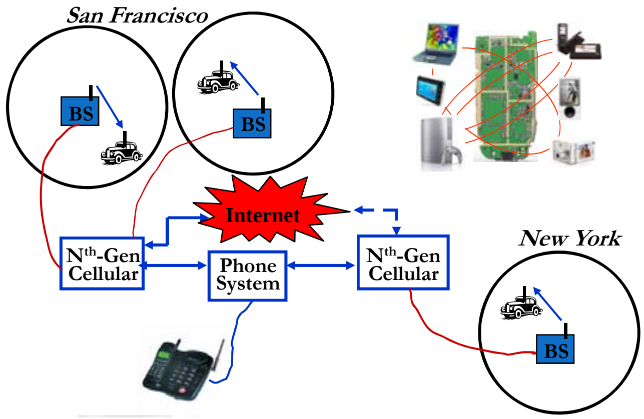
Ubiquitous Communication Among People and Devices



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

Future Cell Phones

Burden for this performance is on the backbone network



Much better performance and reliability than today

- *Gbps rates, low latency, 99% coverage indoors and out*

Future Wifi:

Performance burden also on the (mesh) network

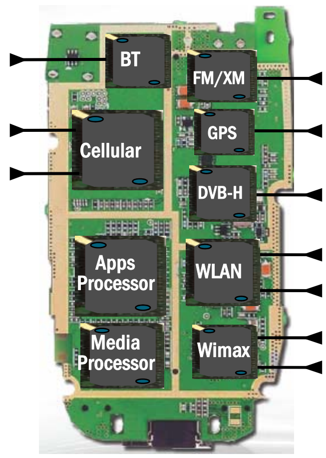
802.11n++

- Streaming video
- Gbps data rates
- High reliability
- Coverage in *every* room

Wireless HDTV and Gaming

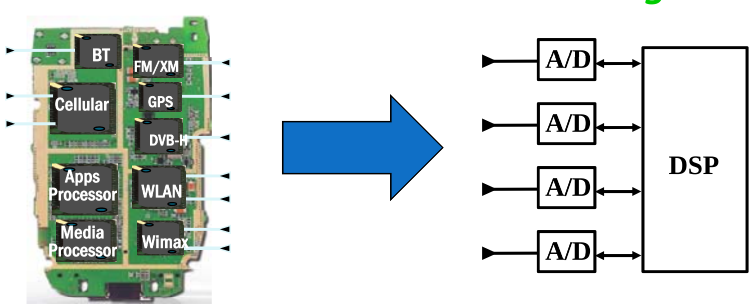
Device Challenges

- Size and Cost
- Power and Heat
- Multiband Antennas
- Multiradio Coexistance
- Integration



Software-Defined Radio:

Is this the solution to the device challenges?



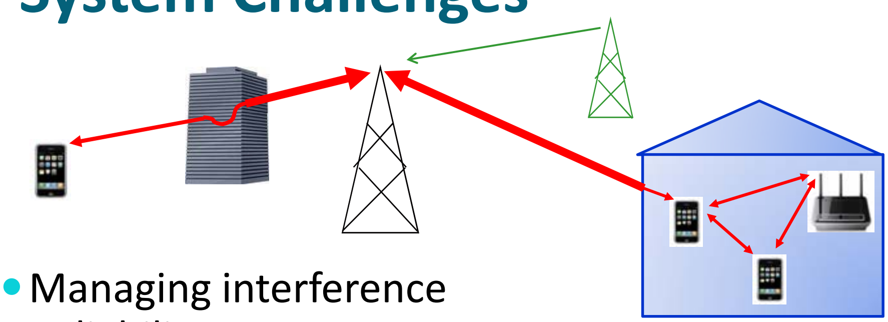
- Wideband antennas and A/Ds span BW of desired signals
- DSP is programmed to process the desired signal based on carrier frequency, signal shape, channel characteristics, etc.
- Avoids specialized hardware

Today, this is not cost, size, or power efficient

Device Solutions

- Silicon evolution will reduce size and power
  - 130nm→95nm →65nm →45nm → 32nm →…
- Circuit design **BREAKTHROUGHS** not anticipated
  - CMOS PA efficiency and power will improve
  - A/D technology will improve
  - Wideband antenna design will improve
  - Tools for digital design will improve
- Room for innovation at the RF/baseband interface
- Dedicated silicon will remain faster, cheaper, and lower power than processor-based designs
  - But less flexible and with most costly development

System Challenges



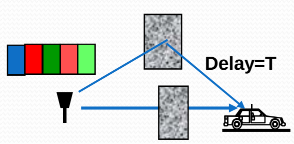
- Managing interference
- Reliability
- High-bandwidth applications
- Scarce spectrum
- Real-time constraints
- Ubiquitous coverage indoors and out

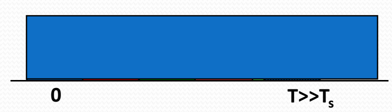
System Solutions

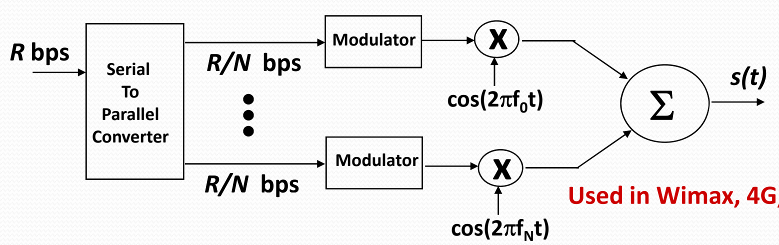
- Better link layer design
  - Low-complexity OFDM and MIMO (PHY wars are over)
  - High-performance modulation and coding
  - Adaptive techniques (in time, space, and frequency)
- Better access and networking techniques
- More efficient use of wireless spectrum
  - Relaying
  - Picocells and Femtocells
  - Cooperation and Cognition
- Cross-Layer Design

Much room for improvement and innovation

Multicarrier Modulation (OFDM)





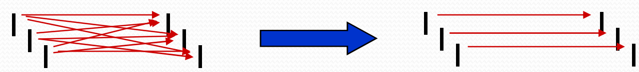


Used in Wimax, 4G, 802.11

- Breaks data into N substreams with Bandwidth B/N
  - Long symbols ($T<<T_s$) removes interference between symbols
- Substream modulated onto separate carriers
- Efficient DSP implementation using IFFTs/FFTs

Multiple Input Multiple Output Systems

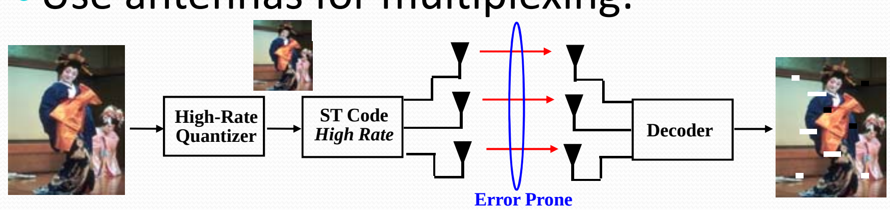
- MIMO systems have multiple (*M*) transmit and receiver antennas



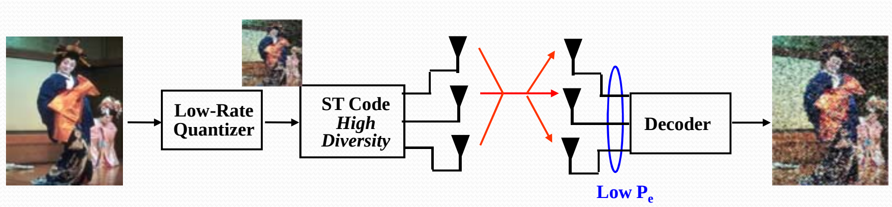
- With perfect channel estimates at TX and RX, decomposes to *M* indep. channels
  - *M*-fold capacity increase over SISO system
    - *Without increasing bandwidth or power!*
  - Demodulation complexity reduction when channel known at the transmitter and receiver
  - Can also use antennas for diversity

Diversity/Multiplexing in MIMO

- Use antennas for multiplexing:



- Use antennas for diversity



How should antennas be used? Depends on end-to-end metric.

MIMO Receiver Complexity

- Receiver Complexity is a problem
  - It affects design time, size, cost, battery life, etc.
- Complexity *Exponential* in Constellation Size/Antenna No.
  - For a full MAP RX

$$C \propto N_I \cdot N_T \cdot 2^{\log_2(M) x N}$$

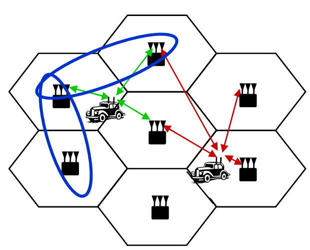
N_I : No. RX Iterations
N_T: No. OFDM Tones
M: Constellation Size
N: No. Antennas

- Reduced complexity receiver options:
  - (Iterative) MMSE, Spherical-decoders, M-Algorithm, etc.
  - Performance/complexity tradeoffs depend on N and M

For 64QAM, 211tones, 6 antennas: $C \propto N_I \times 211 \times 2^{36}$

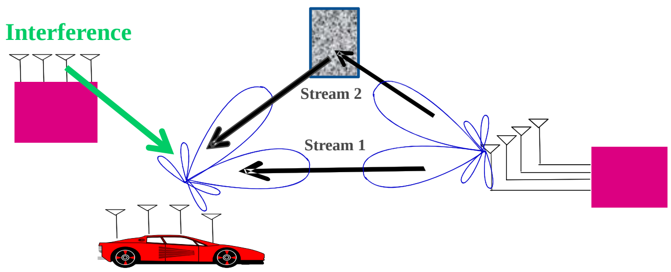
Key area for innovation

MIMO in Wireless Networks



- How should MIMO be *fully* exploited?
- At a base station or Wifi access point
  - MIMO Broadcasting and Multiple Access
- Network MIMO: Form virtual antenna arrays
  - Downlink is a MIMO BC, uplink is a MIMO MAC
  - Can treat “interference” as a known signal or noise
  - Can cluster cells and cooperate between clusters

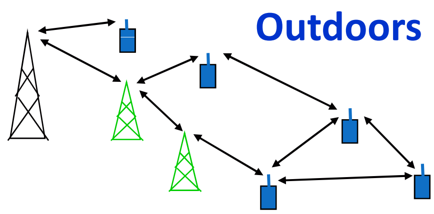
Multiplexing/diversity/interference cancellation tradeoffs in MIMO networks



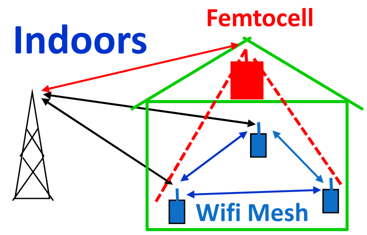
- Spatial multiplexing provides for multiple data streams
- TX beamforming and RX diversity provide robustness to fading
- TX beamforming and RX nulling cancel interference

Optimal use of antennas in wireless networks unknown

Coverage Indoors and Out:
Cellular (Wimax) versus Mesh

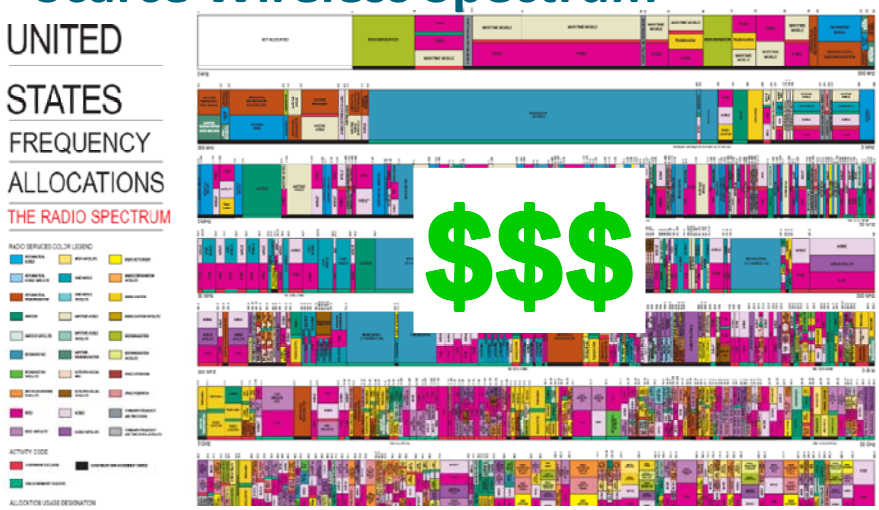


- Cellular has good coverage outdoors
- Relaying increases reliability and range
- Wifi mesh has a *niche* market outdoors
- Hotspots/picocells enhance coverage, reliability, and data rates.
- Multiple frequencies can be leveraged to avoid interference



- Cellular cannot provide reliable indoor coverage
- Wifi networks already ubiquitous in the home
- Alternative is a consumer-installed Femtocell
- Winning solution will depend on many factors

Scarce Wireless Spectrum

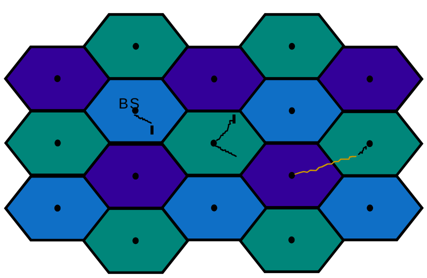


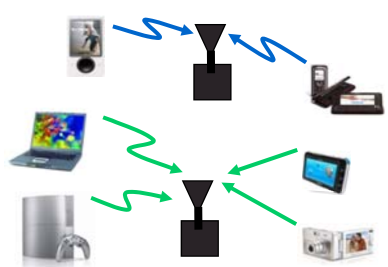
and Expensive

Spectral Reuse

Due to its scarcity, spectrum is *reused*

In licensed bands **and unlicensed bands**





Cellular, Wimax **Wifi, BT, UWB,…**

Reuse introduces interference

Interference: *Friend or Foe?*

- If treated as noise: Foe

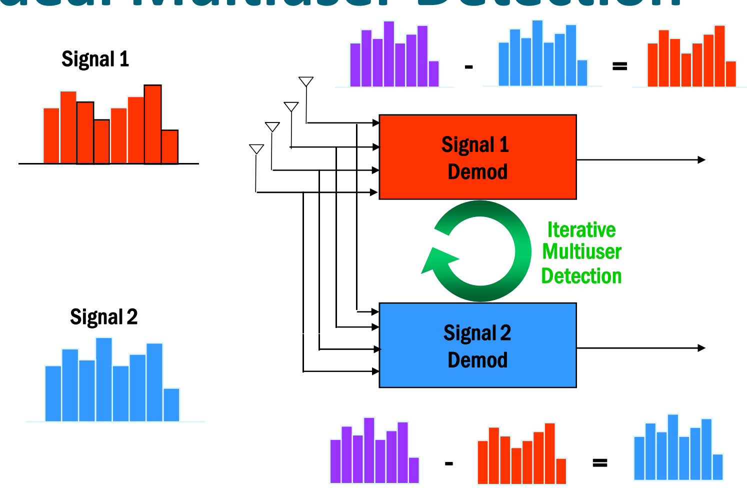
$$SNR = \frac{P}{N + I}$$

Increases BER, reduces capacity

- If decodable: Neither friend nor foe

Multiuser detection can completely remove interference

Ideal Multiuser Detection



Why Not Ubiquitous Today? **Power and A/D Precision**

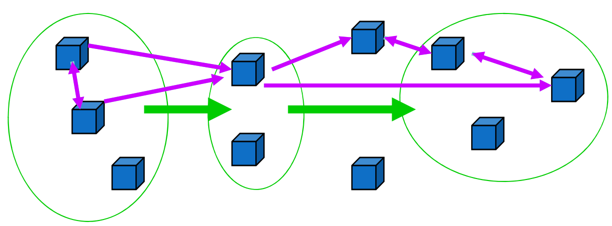
Interference: *Friend or Foe?*

If exploited via cooperation and cognition

Friend

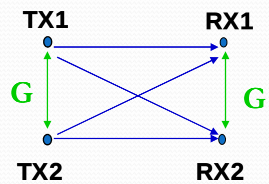
Especially in a network setting

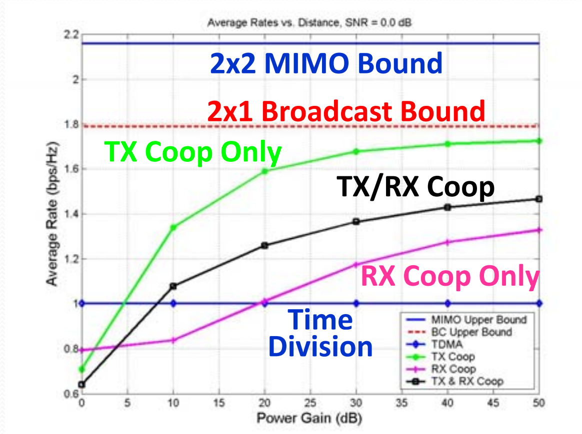
Cooperation in Wireless Networks



- 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, …

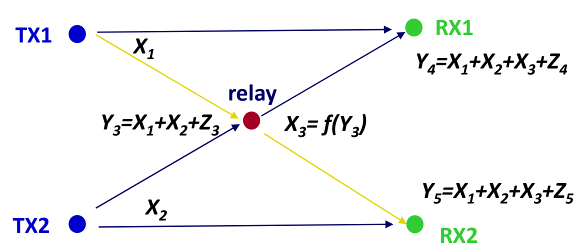
Capacity with Cooperative MIMO





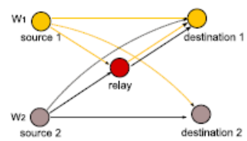
- TX cooperation needs large cooperative channel gain to approach broadcast bound
- 2x2 MIMO bound unapproachable

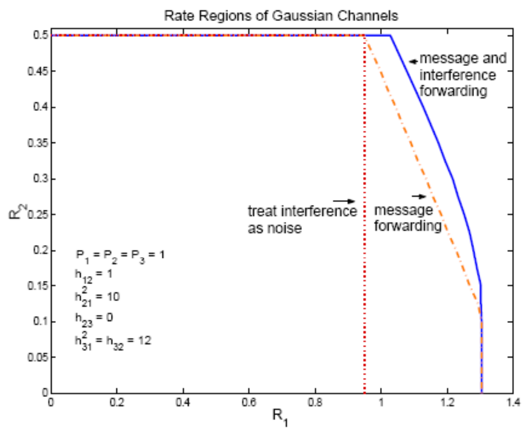
General Relay Strategies



- **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



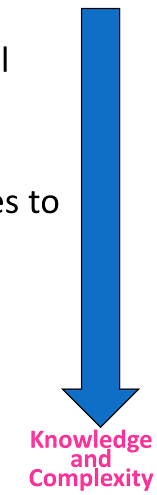


Intelligence beyond Cooperation: *Cognition*

- 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

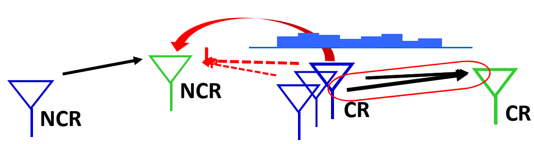
Cognitive Radio Paradigms

- 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



Underlay Systems

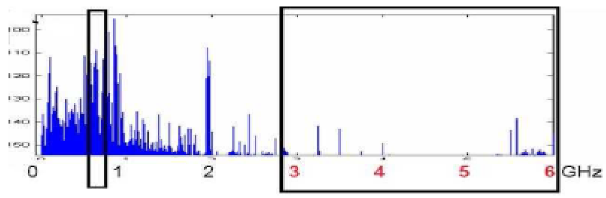
- Cognitive radios determine the interference their transmission causes to noncognitive nodes
  - Transmit if interference below a given threshold



- 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

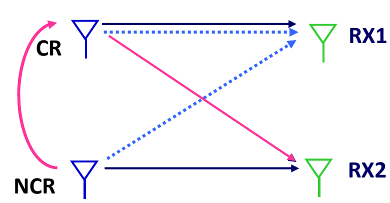
- Measurements indicate that even crowded spectrum is not used across all time, space, and frequencies
  - Original motivation for "cognitive" radios (Mitola'00)



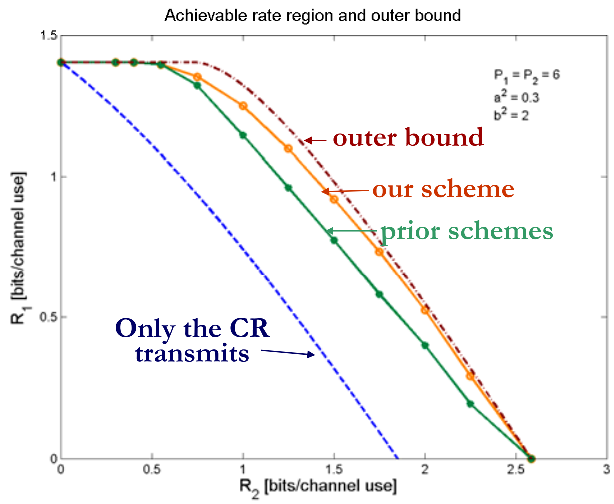
- These holes can be used for communication
  - Interweave CRs periodically monitor spectrum for holes
  - Hole location must be agreed upon between TX and RX
  - Hole is then used for opportunistic communication with minimal interference to noncognitive users

Overlay Cognitive Systems

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

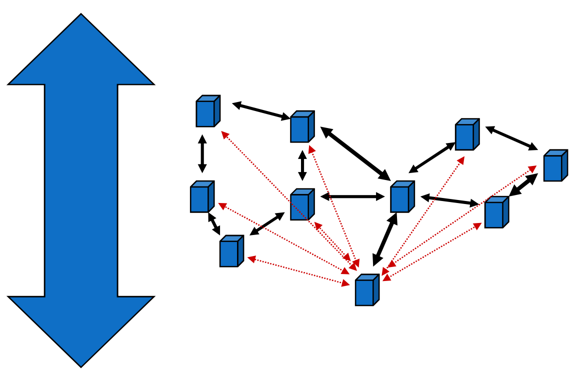


Performance Gains from Cognitive Encoding



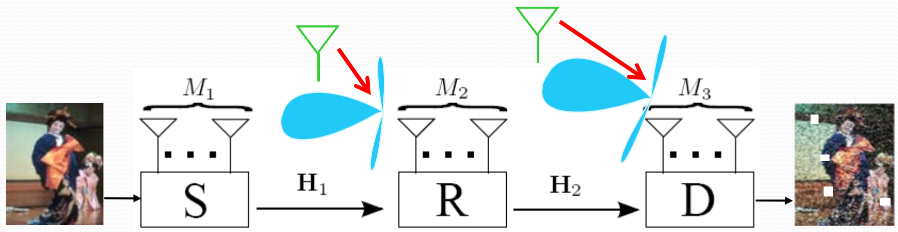
Crosslayer Protocol Design

- Application
- Network
- Access
- Link
- Hardware



Substantial gains in throughput, efficiency, and end-to-end performance from cross-layer design

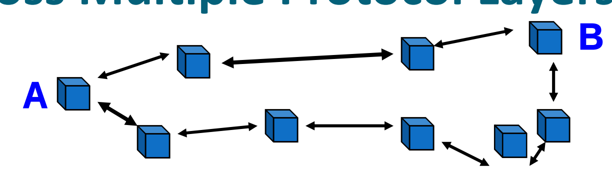
Multiple Antennas in Multihop Networks



- Antennas can be used for multiplexing, diversity, or interference cancellation
  - Cancel M-1 interferers with M antennas
  - Errors occur due to fading, interference, and delay
- What metric should be optimized?

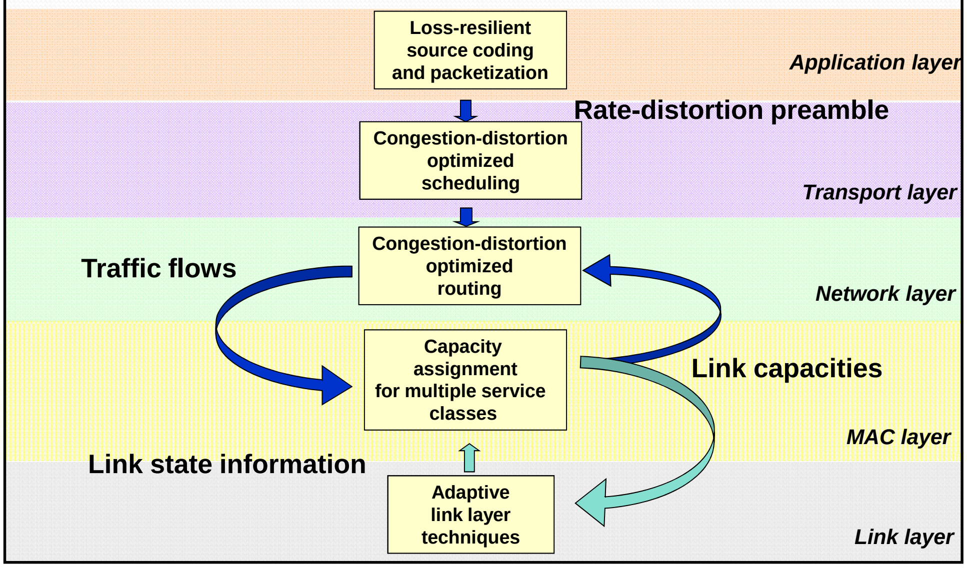
Cross-Layer Design

Delay/Throughput/Robustness across Multiple Protocol Layers

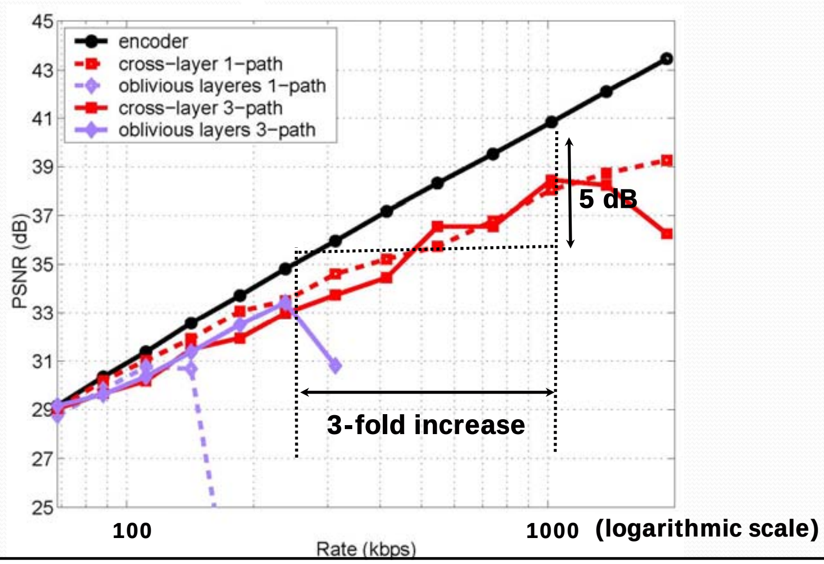


- Multiple routes through the network can be used for multiplexing or reduced delay/loss
  - Spatial dimension of MIMO adds new degree of freedom
- Application can use single-description or multiple description codes
- Can optimize optimal operating point for these tradeoffs to minimize distortion

Cross-layer design for video



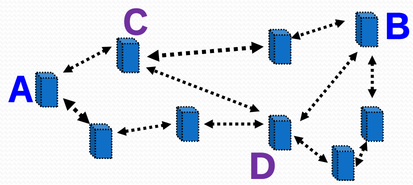
Video streaming performance

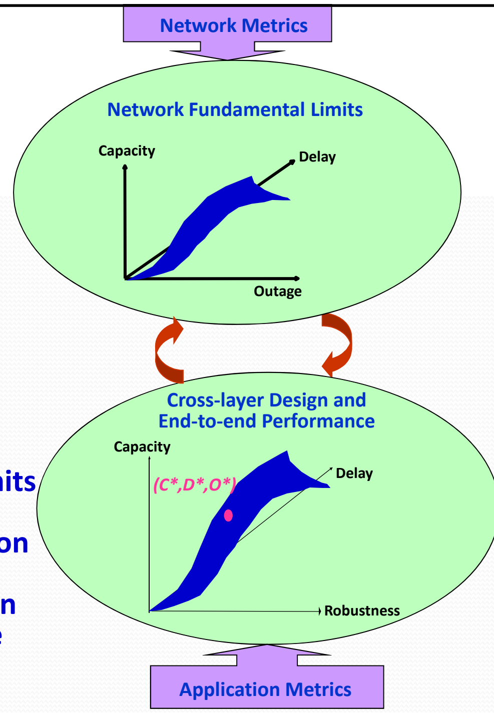


FLoWS

Fundamental Limits
of Wireless Systems

(DARPA Challenge Program)

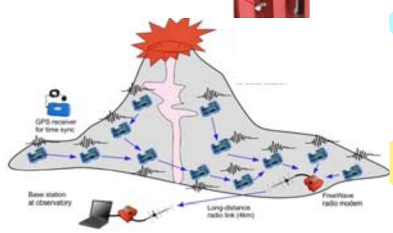


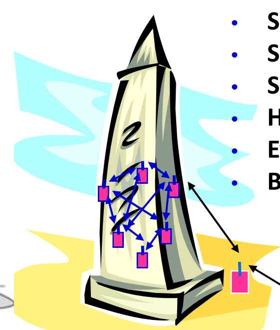


Research Areas

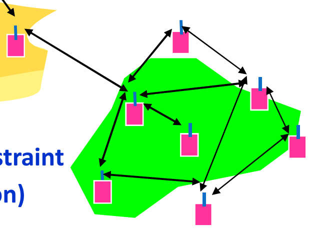
- Fundamental performance limits and tradeoffs
- Node cooperation and cognition
- Adaptive techniques
- Layering and Cross-layer design
- Network/application interface
- End-to-end performance optimization and guarantees

Wireless Sensor Networks





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

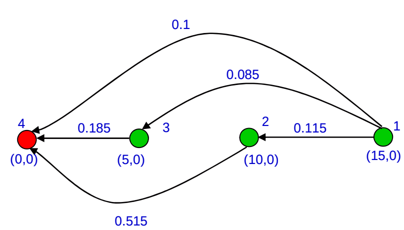


- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices

Cross-Layer Tradeoffs under Energy Constraints

- Hardware
  - All nodes have transmit, sleep, and transient modes
  - Each node can only send a finite number of bits
- Link
  - High-level modulation costs transmit energy but saves circuit energy (shorter transmission time)
  - Coding costs circuit energy but saves transmit energy
- Access
  - Power control impacts connectivity and interference
  - Adaptive modulation adds another degree of freedom
- Routing:
  - Circuit energy costs can preclude multihop routing

Minimum Energy Routing



Red: hub node
Green: relay/source

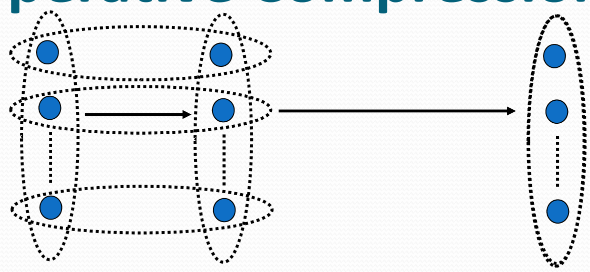
$R_1 = 60\, pps$

$R_2 = 80\, pps$

$R_3 = 20\, pps$

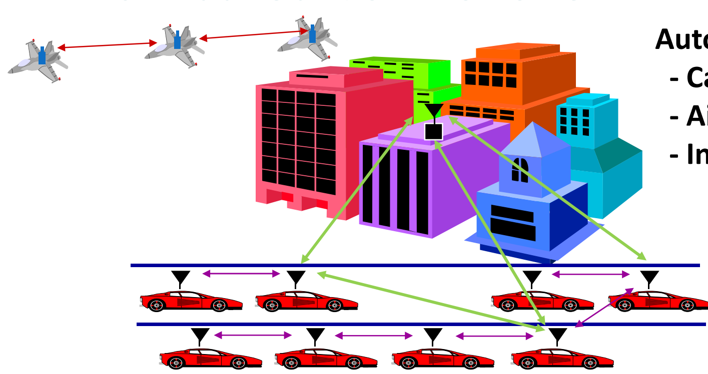
- Optimal routing uses single and multiple hops
- Link adaptation yields additional 70% energy savings

Cooperative Compression



- 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: virtual MIMO vs. relaying

Distributed Control over Wireless



Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

Interdisciplinary design approach

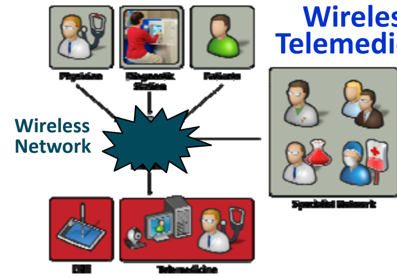
- **Control requires fast, accurate, and reliable feedback.**
- **Wireless networks introduce delay and loss**
- **Need reliable networks and robust controllers**
- **Mostly open problems*: Many design challenges***

Wireless Biomedical Systems

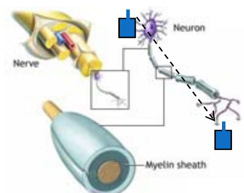
In- Body Wireless Devices

-Sensors/monitoring devices
-Drug delivery systems
-Medical robots
-Neural implants

Wireless Telemedicine



Recovery from Nerve Damage



Challenges being defined

Tech Transfer Challenges

Quantenna Communications

- Communication and network theory can be implemented in a real system in 3-12 months with sufficent $$$
- Information/Communication Theory heavily influence next-gen. wireless systems (mainly at the PHY & MAC layers)
  - Idealized assumptions have been liberating
  - Above PHY/MAC, there is little fundamental theory, which has prevented real breakthroughs
- Industry people read our papers and implement our ideas
- Launching a startup is the best way to do tech transfer
- We need more/better ways to exploit academic innovation

Summary

- The next wave in wireless technology is upon us
- This technology will enable new applications that will change people's lives worldwide
- Design innovation will be needed to meet the requirements of these next-generation systems
- A systems view and interdisciplinary design approach holds the key to these innovations