EE360: Multiuser Wireless Systems and Networks

Lecture 1 Outline

- Course Details
- Course Syllabus
- Course Overview
  - Future Wireless Networks
  - Multiuser Channels (Broadcast/MAC Channels)
  - Spectral Reuse and Interference
  - Cellular Systems
  - Ad-Hoc Networks
  - Cognitive Radio Paradigms
  - Sensor Networks and Green Networks
  - Key Applications

Course Information

People

- Instructor: Andrea Goldsmith, andrea@ee, Packard 371, 5-6932, OHs: MW after class and by appt.
- TA: Nima Soltani, Email: nsoltani@stanford.edu, OHs: around HWs.
- Class Administrator: Pat Oshiro, poshiro@stanford, Packard 365, 3-2681.

*See web or handout for more details

Course Information

Nuts and Bolts

- Prerequisites: EE359
- Course Time and Location: MW 9:30-10:45, Hewlett 102.
- Class Homepage: www.stanford.edu/class/ee360
  - Contains all required reading, handouts, announcements, HWs, etc.
- Class Mailing List: ee360win0910-students (automatic for on-campus registered students).
  - Guest list: send TA email to sign up
- Tentative Grading Policy:
  - 10% Class participation
  - 10% Class presentation
  - 15% Homeworks
  - 15% Paper summaries
  - 50% Project (10% prop, 15% progress report, 25% final report+poster)

Grade Components

- Class participation
  - Read the required reading before lecture/discuss in class
- Class presentation
  - Present a paper related to one of the course topics
  - hw 0: Choose 3 possible high-impact papers, each on a different syllabus topic, by Jan. 18. Include a paragraph for each describing main idea(s), why interesting/high impact
  - Presentations begin Jan. 25.
- HW assignments
  - Two assignments from book or other problems
- Paper summaries
  - Two 2-4 page summaries of several articles
  - Each should be on a different topic from the syllabus

Project

- Term project on anything related to wireless
- Analysis, simulation and/or experiment
  - Must contain some original research
  - 2 can collaborate if project merits collaboration (scope, synergy)
- Must set up website for project
  - Will post proposal, progress report, and final report to website
- Project proposal due Feb 1 at midnight
  - 1-2 page proposal with detailed description of project plan
  - Revised project proposal due Feb 13.
- Progress report: due Feb. 27 at midnight
  - 2-3 page report with introduction of problem being investigated, system description, progress to date, statement of remaining work
- Poster presentations last week of classes (Thurs March 15?)
- Final report due March 19 at midnight

Tentative Syllabus

- Weeks 1-2: Multiuser systems (Chapters 13.4 and 14, additional papers)
- Weeks 3-4: Cellular systems (Chapter 15, additional papers)
- Weeks 5-6: Ad hoc wireless networks (Chapter 16, additional papers)
- Week 7: Cognitive radio networks (papers)
- Week 8: Sensor networks (papers)
- Week 9: Applications & cross-layer design (papers)
- Weeks 10: Additional Topics. Course Summary

See website for details
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 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

Spectral Reuse

Due to its scarcity, spectrum is reused

In licensed bands and unlicensed bands

Cellular, WiMax

Wi-Fi, BT, UWB, ...

Reuse introduces interference

Scarcity Wireless Spectrum

$\text{UNITED} \text{STATES}$

Frequency allocations

Radio spectrum

$\text{$$$} \text{and Expensive}$

Interference: Friend or Foe?

- If treated as noise: Foe
  \[ \text{SNR} = \frac{P}{N + I} \]
  
  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

- 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 toward cell boundary
  - Small cells create a cell within a cell (HetNet)
  - Mobile cooperation via relaying, virtual MIMO, analog network coding.

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, …

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

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?

Beneficial to forward both interference and message
In fact, it can achieve capacity.

**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

**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

**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

Only the CR transmits

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

- 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.

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

- Minimize energy at both the mobile and base station via
  - New Infrastructures: 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

Research indicates that significant savings is possible
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.

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

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

Automated Vehicles

- Cloud
- Handoff
- Fuel cells
- Gas
- Water
- Sensors
- HVAC

Possible Dichotomy for Smart Grid Design

- Encryption, antijam, denial of use, impersonation, cyber-physical security, ...
- Real-time/embedded control, demand-response, resource allocation, fault tolerance, ...
- Sensor networks, HAN, Wi-Fi, WiMax, Cellular, ...
- Electric, gas, and water sensors, HVAC, ...

Key Application: Smart Grids

- Grid Network
- Smart Meter
- IoT
- Smart Grid
- Home Energy
- Environment
- Infrastructure

Economics and Market layer
- Pricing, incentives, markets, ...

Control and Optimization layer
- Real-time/embedded control, demand-response, resource allocation, fault tolerance, ...

Network Layer
- Sensor networks, HAN, Wi-Fi, WiMax, Cellular, ...

Sensing Layer
- Electric, gas, and water sensors, HVAC, ...

Physical Layer
- Encryption, antijam, denial of use, impersonation, cyber-physical security, ...

Interdisciplinary design approach
- Control requires fast, accurate, and reliable feedback.
- Wireless networks introduce delay and loss.
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The brain as a wireless network
- EKG signal reception/modeling
- Signal encoding and decoding
- Nerve network (re)configuration

Doctor-on-a-chip
- Cell phone info repository
- Monitoring, remote intervention and services