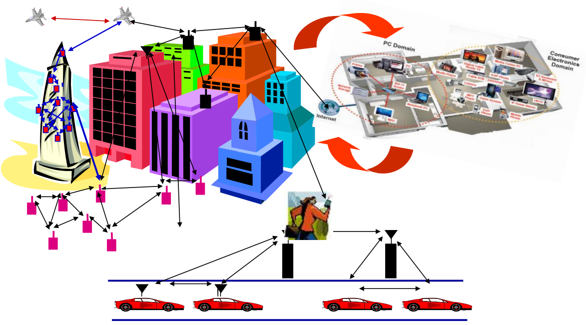
EE 359: Wireless Communications

Professor Andrea Goldsmith



Outline

- Course Basics
- Course Syllabus
- The Wireless Vision
- Technical Challenges
- Current Wireless Systems
- Emerging Wireless Systems
- Spectrum Regulation
- Standards

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: TW (time/place tbd), Email OH's: MW 10-11pm; Discussion: likely T eve.
- Class Administrator: Pat Oshiro, poshiro@stanford, Packard 365, 3-2681. Homework dropoff: Th by 5 pm.

*See web or handout for more details

Course Information
Nuts and Bolts

- Prerequisites: EE279 or equivalent (Digital Communications)
- Required Textbook: *Wireless Communications* (by me), CUP
  - Available at bookstore or Amazon
  - Extra credit for finding typos/mistakes/etc.
  - Supplemental texts on 1 day reserve at Engineering Library.
- Class Homepage: www.stanford.edu/class/ee359
  - All handouts, announcements, homeworks, etc. posted to website
  - "Lectures" link continuously updates topics, handouts, and reading
- Class Mailing List: ee359-aut1112-students@lists (automatic for on-campus registered students).
  - Guest list ee359-aut1112-guest@lists for SCPD and auditors: send Nima email to sign up.
  - Sending mail to ee359-aut1112-staff@lists reaches me and Nima.

Course Information
Policies

- Grading: Two Options
  - No Project (3 units): HW – 30%, 2 Exams – 30%, 40%
  - Project (4 units): HWs- 20%, Exams - 25%, 30%, Project - 25%
- HWs: assigned Wednesday, due following Thursday at 5pm
  - Homeworks lose 33% credit per day late, lowest HW dropped
  - Up to 3 students can collaborate and turn in one HW writeup
  - Collaboration means all collaborators work out all problems together
- Exams:
  - Midterm week of 11/7. (It will likely be scheduled outside class time since the duration is 2 hours.) Final on 12/14 from 8:30-11:30 am.
  - Exams must be taken at scheduled time, no makeup exams

Course Information
Projects

- The term project (for students electing to do a project) is a research project related to any topic in wireless
- Two people may collaborate if you convince me the sum of the parts is greater than each individually
- A 1 page proposal is due 10/28 at 5 pm.
  - 5-10 hours of work typical for proposal
  - Project website must be created and proposal posted there
- The project is due by 5 pm on 12/11 (on website)
- Suggested topics in project handout

Makeup Classes

- There will be no regular lectures 10/17 and 10/19
- Tentatively plan to have makeup lectures on 10/19 afternoon and 10/21 (food provided):
  - Can everyone make these times/days?
  - Extra OHs the week of makeup lectures

Course Syllabus

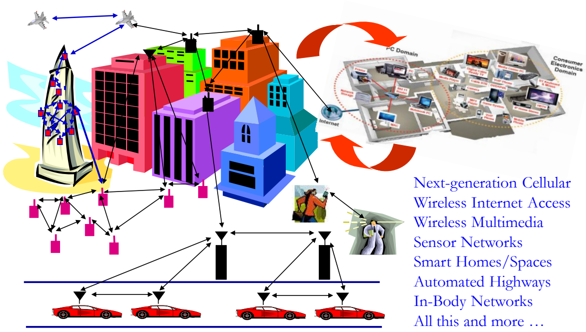
- Overview of Wireless Communications
- Path Loss, Shadowing, and Fading Models
- Capacity of Wireless Channels
- Digital Modulation and its Performance
- Adaptive Modulation
- Diversity
- MIMO Systems
- Multicarrier Modulation
- Spread Spectrum
- Multiuser Communications & Wireless Networks

Wireless History

- Ancient Systems: Smoke Signals, Carrier Pigeons, …
- Radio invented in the 1880s by Marconi
- Many sophisticated military radio systems were developed during and after WW2
- Cellular has enjoyed exponential growth since 1988, with almost 3 billion users worldwide today
  - Ignited the wireless revolution
  - Voice, data, and multimedia becoming ubiquitous
  - Use in third world countries growing rapidly
- Wifi also enjoying tremendous success and growth
  - Wide area networks (e.g. Wimax) and short-range systems other than Bluetooth (e.g. UWB) less successful

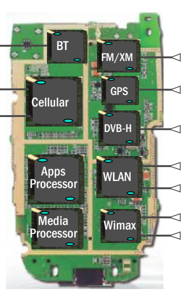
Future Wireless Networks

Ubiquitous Communication Among People and Devices



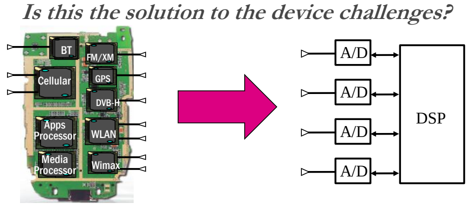
Challenges

- Network Challenges
  - Scarce spectrum
  - Demanding/diverse applications
  - Reliability
  - Ubiquitous coverage
  - Seamless indoor/outdoor operation
- Device Challenges
  - Size, Power, Cost
  - Multiple Antennas in Silicon
  - Multiradio Integration
  - Coexistance



Software-Defined (SD) Radio:

Is this the solution to the device challenges?



- Wideband antennas and A/Ds span BW of desired signals
- DSP programmed to process desired signal: no specialized HW

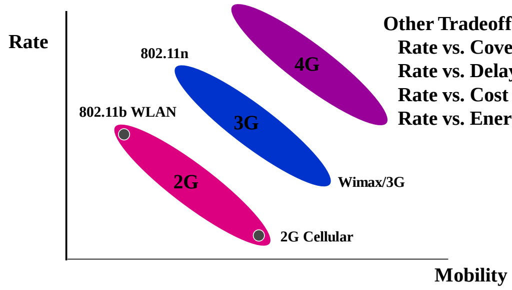
Today, this is not cost, size, or power efficient

Compressed sensing may be a solution for sparse signals

Evolution of Current Systems

- Wireless systems today
  - 3G Cellular: ~200-300 Kbps.
  - WLANs: ~450 Mbps (and growing).
- Next Generation is in the works
  - 4G Cellular: OFDM/MIMO
  - 4G WLANs: Wide open, 3G just being finalized
- Technology Enhancements
  - Hardware: Better batteries. Better circuits/processors.
  - Link: More bandwidth, more antennas, better modulation and coding, adaptivity, cognition.
  - Network: better resource allocation, cooperation, relaying, femtocells.
  - Application: Soft and adaptive QoS.

Future Generations



Other Tradeoffs:
- Rate vs. Coverage
- Rate vs. Delay
- Rate vs. Cost
- Rate vs. Energy

Fundamental Design Breakthroughs Needed

Multimedia Requirements

	Voice	Data	Video
Delay	<100ms	-	<100ms
Packet Loss	<1%	0	<1%
BER	10^{-3}	10^{-6}	10^{-6}
Data Rate	8-32 Kbps	10-1000 Mbps	10-1000 Mbps
Traffic	Continuous	Bursty	Continuous

One-size-fits-all protocols and design do not work well

Wired networks use this approach, with poor results

Quality-of-Service (QoS)

- QoS refers to the requirements associated with a given application, typically rate and delay requirements.
- It is hard to make a one-size-fits all network that supports requirements of different applications.
- Wired networks often use this approach with poor results, and they have much higher data rates and better reliability than wireless.
- QoS for all applications requires a cross-layer design approach.

Crosslayer Design

- Application
- Network
- Access
- Link
- Hardware

Delay Constraints
Rate Constraints
Energy Constraints

Adapt across design layers
Reduce uncertainty through scheduling
Provide robustness via diversity

Current Wireless Systems

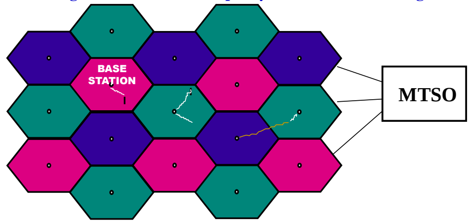
- Cellular Systems
- Wireless LANs
- Wimax
- Satellite Systems
- Paging Systems
- Bluetooth
- Zigbee radios

Cellular Phones

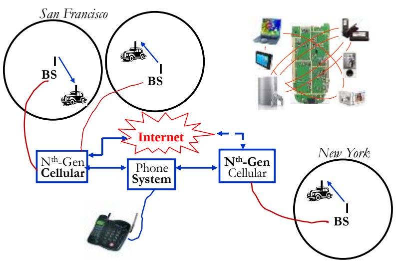
Everything Wireless in One Device

Cellular Systems: Reuse channels to maximize capacity

- Geographic region divided into cells
- Frequency/timeslots/codes/ reused at spatially-separated locations.
- Co-channel interference between same color cells.
- Base stations/MTSOs coordinate handoff and control functions
- Shrinking cell size increases capacity, as well as networking burden



Cellular Networks



Future networks want better performance and reliability

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

3G Cellular Design:

Voice and Data

- Data is bursty, whereas voice is continuous
  - Typically require different access and routing strategies
- 3G "widens the data pipe":
  - 384 Kbps (802.11n has 100s of Mbps).
  - Standard based on wideband CDMA
  - Packet-based switching for both voice and data
  - 3G cellular popular in Asia and Europe
- Evolution of existing systems in US (2.5G++)
  - GSM+EDGE, IS-95(CDMA)+HDR
  - 100 Kbps may be enough
  - Dual phone (2/3G+Wifi) use growing (iPhone, Google)
- What is beyond 3G?

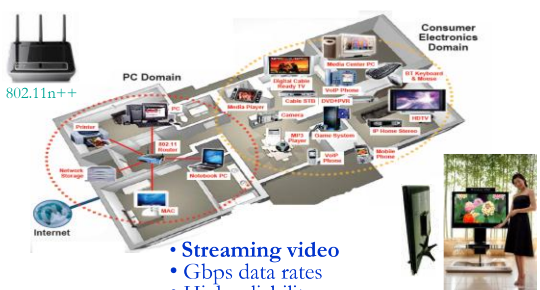
The trillion dollar question

4G/LTE/IMT Advanced

- Much higher peak data rates (50-100 Mbps)
- Greater spectral efficiency (bits/s/Hz)
- Flexible use of up to 100 MHz of spectrum
- Low packet latency (<5ms).
- Increased system capacity
- Reduced cost-per-bit
- Support for multimedia

Wifi Networks

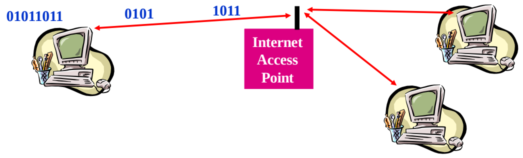
Multimedia Everywhere, Without Wires



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

Wireless HDTV and Gaming

Wireless Local Area Networks (WLANs)



- WLANs connect "local" computers (100m range)
- Breaks data into packets
- Channel access is shared (random access)
- Backbone Internet provides best-effort service
  - Poor performance in some apps (e.g. video)

Wireless LAN Standards

- 802.11b (Old – 1990s)
  - Standard for 2.4GHz ISM band (80 MHz)
  - Direct sequence spread spectrum (DSSS)
  - Speeds of 11 Mbps, approx. 500 ft range
- 802.11a/g (Middle Age– mid-late 1990s)
  - Standard for 5GHz band (300 MHz)/also 2.4GHz
  - OFDM in 20 MHz with adaptive rate/codes
  - Speeds of 54 Mbps, approx. 100-200 ft range

Many WLAN cards have all 3 (a/b/g)

- 802.11n (young pup) What's next? 802.11ac/ad
  - Standard in 2.4 GHz and 5 GHz band
  - Adaptive OFDM /MIMO in 20/40 MHz (2-4 antennas)
  - Speeds up to 600Mbps, approx. 200 ft range
  - Other advances in packetization, antenna use, etc.

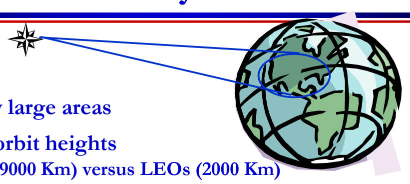
Wimax (802.16)

- Wide area wireless network standard
  - System architecture similar to cellular
  - Called "3.xG" (e.g. Sprint EVO), evolving into 4G
- OFDM/MIMO is core link technology
- Operates in 2.5 and 3.5 GHz bands
  - Different for different countries, 5.8 also used.
  - Bandwidth is 3.5-10 MHz
- Fixed (802.16d) vs. Mobile (802.16e) Wimax
  - Fixed: 75 Mbps max, up to 50 mile cell radius
  - Mobile: 15 Mbps max, up to 1-2 mile cell radius

WiGig and Wireless HD

- New standards operating in 60 GHz band
- Data rates of 7-25 Gbps
- Bandwidth of around 10 GHz (unregulated)
- Range of around 10m (can be extended)
- Uses/extends 802.11 MAC Layer
- Applications include PC peripherals and displays for HDTVs, monitors & projectors

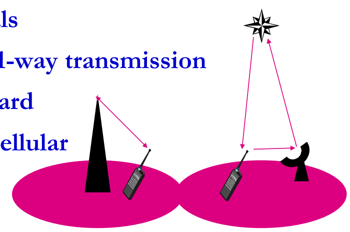
Satellite Systems



- Cover very large areas
- Different orbit heights
  - GEOs (39000 Km) versus LEOs (2000 Km)
- Optimized for one-way transmission
  - Radio (XM, Sirius) and movie (SatTV, DVB/S) broadcasts
  - Most two-way systems struggling or bankrupt
- Global Positioning System (GPS) use growing
  - Satellite signals used to pinpoint location
  - Popular in cell phones, PDAs, and navigation devices

Paging Systems

- Broad coverage for short messaging
- Message broadcast from all base stations
- Simple terminals
- Optimized for 1-way transmission
- Answer-back hard
- Overtaken by cellular



Bluetooth

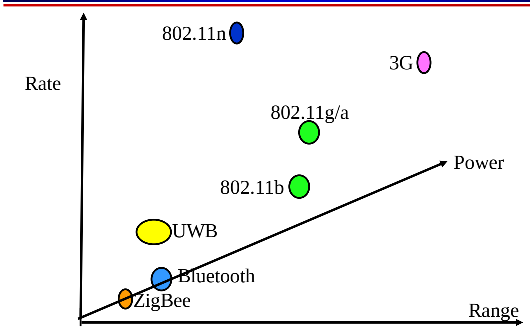
- Cable replacement RF technology (low cost)
- Short range (10m, extendable to 100m)
- 2.4 GHz band (crowded)
- 1 Data (700 Kbps) and 3 voice channels, up to 3 Mbps
- Widely supported by telecommunications, PC, and consumer electronics companies
- Few applications beyond cable replacement

IEEE 802.15.4/ZigBee Radios

- Low-Rate WPAN
- Data rates of 20, 40, 250 Kbps
- Support for large mesh networking or star clusters
- Support for low latency devices
- CSMA-CA channel access
- Very low power consumption
- Frequency of operation in ISM bands

Focus is primarily on low power sensor networks

Tradeoffs



Scarce Wireless Spectrum

and Expensive

Spectrum Regulation

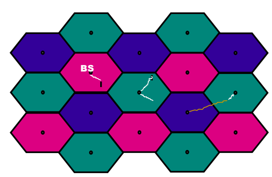
- Spectrum a scarce public resource, hence allocated
- Spectral allocation in US controlled by FCC (commercial) or OSM (defense)
- FCC auctions spectral blocks for set applications.
- Some spectrum set aside for universal use
- Worldwide spectrum controlled by ITU-R
- Regulation is a necessary evil.

Innovations in regulation being considered worldwide, including underlays, overlays, and cognitive radios

Spectral Reuse

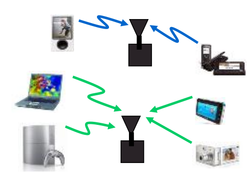
Due to its scarcity, spectrum is *reused*

In licensed bands



Cellular, Wimax

and unlicensed bands



Wifi, BT, UWB,…

Reuse introduces interference

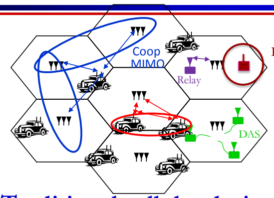
Interference: *Friend or Foe?*

If exploited via
cooperation and cognition

Friend

Especially in a network setting

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
  - Femtocells create a cell within a cell
  - Mobile cooperation via relays, virtual MIMO, network coding.

Standards

- Interacting systems require standardization
- Companies want their systems adopted as standard
  - Alternatively try for de-facto standards
- Standards determined by TIA/CTIA in US
  - IEEE standards often adopted
  - Process fraught with inefficiencies and conflicts
- Worldwide standards determined by ITU-T
  - In Europe, ETSI is equivalent of IEEE

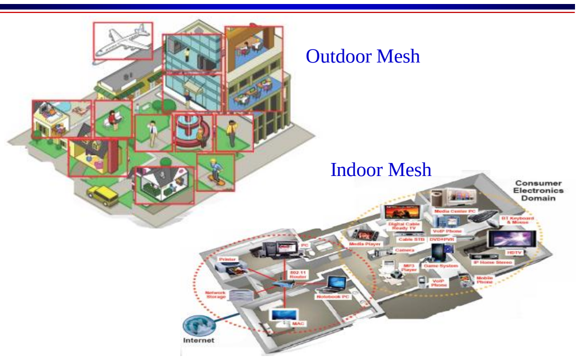
Standards for current systems are summarized in Appendix D.

Emerging Systems*

- 4th generation cellular (4G)
  - OFDMA is the PHY layer
  - Other new features and bandwidth still in flux
- Ad hoc/mesh wireless networks
- Cognitive radios
- Sensor networks
- Distributed control networks
- Biomedical networks

***Can have a bonus lecture on this topic late in the quarter if there is interest**

Ad-Hoc/Mesh Networks



Design Issues

- Ad-hoc networks provide a flexible network infrastructure for many emerging applications.
- The capacity of such networks is generally unknown.
- Transmission, access, and routing strategies for ad-hoc networks are generally ad-hoc.
- Crosslayer design critical and very challenging.
- Energy constraints impose interesting design tradeoffs for communication and networking.

Cognitive Radios

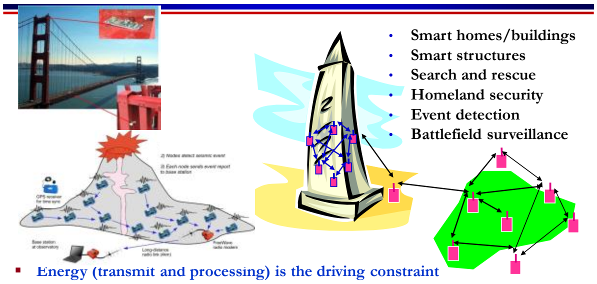
- Cognitive radios can support new wireless users in existing crowded spectrum
  - Without degrading performance of existing users
- Utilize advanced communication and signal processing techniques
  - Coupled with novel spectrum allocation policies
- Technology could
  - Revolutionize the way spectrum 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

Wireless Sensor Networks
Data Collection and Distributed Control



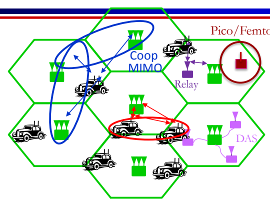
- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance

- 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

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.

Green" Cellular Networks

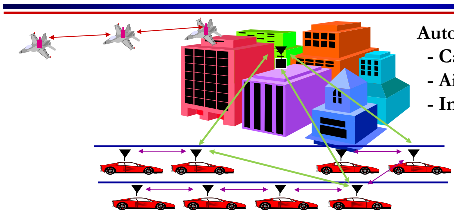


How should cellular systems be redesigned for minimum energy?

Research indicates that significant 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

Distributed Control over Wireless



Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

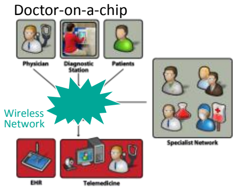
Interdisciplinary design approach

- 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*

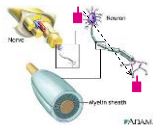
Applications in Health, Biomedicine and Neuroscience

Body-Area Networks

Doctor-on-a-chip



Neuro/Bioscience
- EKG signal reception/modeling
- Information science
- Nerve network (re)configuration
- Implants to monitor/generate signals
-In-brain sensor networks



Recovery from Nerve Damage

Main Points

- The wireless vision encompasses many exciting systems and applications
- Technical challenges transcend across all layers of the system design.
- Cross-layer design emerging as a key theme in wireless.
- Existing and emerging systems provide excellent quality for certain applications but poor interoperability.
- Standards and spectral allocation heavily impact the evolution of wireless technology