Acknowledgement

- Slides derived from class material posted by Dr. A. Goldsmith
- [www.stanford.edu/class/ee359/lectures.html](http://www.stanford.edu/class/ee359/lectures.html)
- See also: A. Goldsmith, *Wireless Communications*, Cambridge Press

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

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

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
  - Coexistence
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

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
  - 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

Rate

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

Mobility

Fundamental Design Breakthroughs Needed

Multimedia Requirements

<table>
<thead>
<tr>
<th></th>
<th>Voice</th>
<th>Data</th>
<th>Video</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay</td>
<td>&lt;100ms</td>
<td>-</td>
<td>&lt;100ms</td>
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<tr>
<td>Packet Loss</td>
<td>&lt;1%</td>
<td>0</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>BER</td>
<td>10^{-3}</td>
<td>10^{-6}</td>
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<tr>
<td>Data Rate</td>
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<td>10-1000 Mbps</td>
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<tr>
<td>Traffic</td>
<td>Continuous</td>
<td>Bursty</td>
<td>Continuous</td>
</tr>
</tbody>
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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 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?
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 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

- **802.11n (young pup)**
  - 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.

- **What’s next?** 802.11ac/ad
  - Many WLAN cards have all 3 (a/b/g)
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

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

**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

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
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

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

Wireless Sensor Networks

*Data Collection and Distributed Control*

- 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

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

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