LECTURE 1

Introduction
Things we need to know

- CS 164
  - Qualitative idea of telecommunication networks and protocols – the OSI stack
  - what TCP/IP is, etc.
  - Routing protocols
Broad overview of course contents

- Wireless Systems
  - Wireless Wide Area Networks (WWANs)
  - Wireless Metro Area Networks (WMANs)
  - Wireless Local Area Networks (WLANs)
  - Wireless Personal Area Networks (WPANs)
  - Ad hoc and mesh networks
    Beware of Acronyms!

- Lower Layers
  - Physical Layer (PHY)
    - Radio Propagation
    - Modulation
  - Access layer (MAC)
  - Deployment

- Higher Layers
  - Routing
  - Transport
  - Mobility Management (MM)
Course Objectives

- Learn architectural differences between various wireless systems
- Examine how wireless affects protocol design and development
- Uncover network operation, deployment, and application issues
Textbook and references

- **Textbook**
  - *Mobile Communications 2nd edition*, Jochen Schiller, Addison Wesley
  - However, I may draw things from other sources.
  - Refer to slides – should have the content you are responsible for.

- **Other references**
  - Papers from journals and magazines
  - *Principles of Wireless Networks* – Kaveh Pahlavan and Prashant Krishnamurthy, Pearson
Contact

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Grading

- Homework 10%
- Labs 10%
- 3 Quizzes 15% each
  - We will choose the best two.
- Project 20%
- Final 30%

Undergraduates?
Labs and Project

- Lab attendance is mandatory for first 6 weeks.
  - You will lose points for each lab missed.
- First six labs: you will do ns3 simulations
  - Simple experiments
  - Learn the simulator.
- Last four labs – project
  - Will be assigned by Week 6
  - No groups – do this individually.
  - No cooperation whatsoever.
  - Take help from TAs as needed – attend labs as needed.
Homework

- Pick up in lab – turn in next lab.
- In the last four weeks, you will have the option of e-mailing a pdf to your TAs if you cannot attend.
- We will also post it on web.
Clarity and Legibility are Very Important

- There will be no credit for vague answers or unclear steps
- I should be able to understand what you were trying to do without your verbal explanation later
INTRODUCTION TO WIRELESS SYSTEMS

Quick Overview
Wireless Communication Systems

- **Wireless communication system**
  - Any electrical communication system that uses a naturally occurring communication channel, such as air, water, earth.

- **Examples:**
  - Cell phone, sonar, ground penetrating radar
  - Broadcast: (one way)
    - Radio, TV, pagers, satellite TV
  - Two Way:
    - Walkie talkie, cell phones, satellite phones, WiFi, Bluetooth

- Fundamentally different from wired networks
Mobile Vs. Wireless

- Mobile and Wireless are not interchangeable
- **Mobile** and **wireless** communication systems
  - Communicate over the air via radio-waves
  - Support some form of user mobility

<table>
<thead>
<tr>
<th>Mobile</th>
<th>Wireless</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>✗</td>
<td>✗</td>
<td>Stationary computer, pay phone</td>
</tr>
<tr>
<td>✗</td>
<td>✓</td>
<td>Wireless local loop</td>
</tr>
<tr>
<td>✓</td>
<td>✗</td>
<td>Calling card, call forwarding</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>Cell phone, laptop with WLAN</td>
</tr>
</tbody>
</table>
Classification of Wireless Systems

Based on Coverage
- Wireless Wide Area Networks
- Wireless Metro Area Networks
- Wireless Local Area Networks
- Wireless Personal Area Networks

Based on Topology
- Infrastructure
- Ad Hoc

Based on Mobility
- Fixed
- Stationary
- Portable
- Mobile
Classification of Wireless Systems

- Wireless Networks
  - Based on Topology
    - Infrastructure
      - Coverage
        - Wide Area
    - Ad Hoc
      - Coverage
        - Personal Area - Single Hop
        - Local Area - Multihop/Mesh

Typically use unlicensed spectrum
Classification based on data rates and technologies

- **Wide Area Network (WAN)**
  - Expensive licensed spectrum
  - Voice-oriented access

- **WLAN**
  - High speed unlicensed
  - Data-oriented access

- **WPAN**
  - Ad-hoc unlicensed
  - Random access

- **Gigabit Wireless**
  - OFDM/DSSS

- **Bluetooth/Zigbee**
  - FHSS/DSSS

- **Vehicle**
  - Outdoor
  - Walk
  - Fixed

- **Walk**
  - Outdoor
  - Fixed

- **Fixed**
  - Indoor
  - Walk
  - Fixed

**User bit rate in Mbps**

- 0.01
- 0.1
- 1
- 10
- 100
- 1000
Traditional Wired Networks
Positioning of Wireless Networks

Additional fixed components for wireless infrastructure

Traditional fixed telephone/data network infrastructure

Ad hoc clusters
Infrastructure Topology

- **Basics**
  - A wired (fixed) infrastructure supports communications between wireless devices and between wireless devices and fixed devices.

- **Base Stations (BSs) or Access Points (APs)** form the point of access to the network:
  - Each BS covers an area called a “cell”
  - Multiple BSs are interconnected to cover a larger geographical area.

- **Star topology**
  - The BS or AP is the hub
  - Any communication from a wireless device to another has to be sent through the BS or AP
  - The BS or AP manages user access to the network.
What is extra?

- **Wireless transceivers**
  - Base stations — BSs and Access points — APs
  - Mobile stations - MSs

- **Spectrum**
  - Frequency bands for uplink and downlink
  - Air interface

- **Management Entities**
  - Mobility management
  - Power management
  - Radio resource management
  - Security

- **Deployment**
  - Frequency reuse
  - Network design
Examples of Infrastructure Wireless Networks

- **Wide area**
  - Voice oriented - Cellular telephone systems
  - Data oriented - Mobile data systems

- **Local Area**
  - Voice oriented - Wireless PBXs
  - Cordless phones
  - Data Oriented - Wireless LANs
History of Wireless Voice Networks

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970s</td>
<td>Exploration of first generation mobile radio at Bell Labs</td>
</tr>
<tr>
<td>Late 1970s</td>
<td>First generation cordless phones</td>
</tr>
<tr>
<td>1982</td>
<td>Exploration of second generation digital cordless CT-2</td>
</tr>
<tr>
<td>1982</td>
<td>Deployment of first analog cellular system: NMT</td>
</tr>
<tr>
<td>1983</td>
<td>Deployment of first US analog cellular system: AMPS</td>
</tr>
<tr>
<td>1983</td>
<td>Exploration of 2G digital cellular GSM</td>
</tr>
<tr>
<td>1985</td>
<td>Exploration of wireless PBXs and DECT</td>
</tr>
<tr>
<td>1988</td>
<td>Initiation of GSM development</td>
</tr>
<tr>
<td>1988</td>
<td>Initiation of IS-54 development</td>
</tr>
<tr>
<td>1988</td>
<td>Exploration of Qualcomm’s CDMA technology</td>
</tr>
<tr>
<td>1991</td>
<td>Deployment of GSM</td>
</tr>
<tr>
<td>1993</td>
<td>Deployment of PHS/PHP and initiation of IS-95</td>
</tr>
<tr>
<td>1995</td>
<td>PCS Band auction</td>
</tr>
<tr>
<td>2002</td>
<td>3G Networks</td>
</tr>
<tr>
<td>2011 and beyond</td>
<td>Voice over LTE (VoLTE), Smartphones</td>
</tr>
</tbody>
</table>
The Cellphone Industry

- **Mobile phone systems**
  - Support communication to mobile users via wireless radio channel

- **Fastest growing technical device EVER!**
  - **Variety of systems**
    - 4.3 Billion Connections (Q2 2009)
    - Analog: NMT, AMPS, TACS
    - Digital: GSM, USDC, IS-95 (cellular CDMA), PDC

- **Scope of services and coverage areas growing**
  - Focus now on wireless data, apps, and location aware services

![Graph showing # of Connections (GSM = 3.4 Billion)](Q2 2009)

Source: GSMA
Example: 4G Data Rates in US Airports

Data Source: RootMetrics/CNN (2014)
US Statistics

34% of Households are “Wireless Only”

Annual Total Wireless Revenues in 2012: $178.4 Billion
Annual Revenues from Data Traffic in 2012: $68.3 Billion

Data Source: CTIA - http://www.ctia.org/advocacy/research/index.cfm/AID/10323
Generations of mobile communications

<table>
<thead>
<tr>
<th>Feature/ Decade</th>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
<th>2010s</th>
<th>2020s</th>
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</thead>
<tbody>
<tr>
<td>Generation</td>
<td>First</td>
<td>Second</td>
<td>Third</td>
<td>Fourth</td>
<td>Fifth</td>
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<tr>
<td>Keywords</td>
<td>Analog</td>
<td>Digital</td>
<td>Global World Standards;</td>
<td>MIMO, High data rate; IP-Based</td>
<td>Cognitive? Open spectrum? high mobility</td>
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<tr>
<td></td>
<td></td>
<td>Personal</td>
<td></td>
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<tr>
<td>Multiple</td>
<td>FDMA</td>
<td>TDMA</td>
<td>CDMA, OFDM</td>
<td>OFDMA</td>
<td>Mixed?</td>
</tr>
<tr>
<td>Access</td>
<td></td>
<td>CDMA</td>
<td></td>
<td></td>
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<tr>
<td>Cellular</td>
<td>Analog Cellular</td>
<td>Digital</td>
<td>UMTS</td>
<td>LTE, WiMax</td>
<td>5G-Cellular, ITS</td>
</tr>
<tr>
<td>Systems</td>
<td></td>
<td>Cellular</td>
<td>Cellular</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>cdma2000 (3G-Cellular) Rates</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>approaching 10Mbps</td>
<td></td>
<td></td>
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<tr>
<td>Local/Home</td>
<td>Analog Cordless</td>
<td>Digital</td>
<td>Digital Cordless</td>
<td>Min. data rate &gt; 100 Mbps</td>
<td>Minimum Data rate Gbps?</td>
</tr>
<tr>
<td>systems</td>
<td></td>
<td>Cordless</td>
<td></td>
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<tr>
<td>Data Systems</td>
<td>Mobile Data</td>
<td>Mobile Data</td>
<td>3G Data, 802.11b, a, g, n</td>
<td>4G Data, 60 GHz WLANs? UWB?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Early WLAN</td>
<td>Early WLAN</td>
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</tbody>
</table>
An evolutionary view of wireless technologies

<table>
<thead>
<tr>
<th>Year</th>
<th>1G Analog</th>
<th>2G Digital TDMA/CDMA</th>
<th>3G Cellular CDMA</th>
<th>4G LTE-Advanced OFDMA/MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980s</td>
<td>1G Analog FM/FDMA</td>
<td>Cellular Overlay CDPD</td>
<td>DSS/FHSS DECT - TDMA</td>
<td>4G LTE OFDMA/MIMO</td>
</tr>
<tr>
<td></td>
<td>Independent Mobile Data</td>
<td>2G Digital TDMA/CDMA</td>
<td>3G Cellular CDMA</td>
<td>4G LTE-Advanced OFDMA/MIMO</td>
</tr>
<tr>
<td>1990s</td>
<td>Analog Cordless Phone FM/FDMA</td>
<td>Digital Cordless TDMA</td>
<td>DSS/FHSS DECT - TDMA</td>
<td>4G WiMax OFDMA/MIMO</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.11 DSSS/FHSS</td>
<td>IEEE 802.11b CCK/DSSS</td>
<td>IEEE 802.11a/g OFDM</td>
<td>IEEE 802.11n OFDM/MIMO</td>
</tr>
<tr>
<td>2000s</td>
<td>IEEE 802.15.1 Bluetooth/FHSS</td>
<td>IEEE 802.15.3 UWB/OFDM/DSSS</td>
<td>IEEE 802.15.4 Zigbee/DSSS</td>
<td>60 GHz Gigabit UWB</td>
</tr>
<tr>
<td></td>
<td>IEEE 802.15.4 Zigbee/DSSS</td>
<td>IEEE 802.15.6 BAN</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## History of Wireless Data

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>Diffused Infrared (IBM Labs in Switzerland)</td>
</tr>
<tr>
<td>1980</td>
<td>Spread Spectrum using SAW Devices (HP Labs in California)</td>
</tr>
<tr>
<td>Early 80s</td>
<td>Wireless modems (Data Radio)</td>
</tr>
<tr>
<td>1983</td>
<td>ARDIS (Motorola/IBM)</td>
</tr>
<tr>
<td>1985</td>
<td>ISM Bands for Spread Spectrum Applications</td>
</tr>
<tr>
<td>1986</td>
<td>Mobitex (Swedish Telecom and Ericsson)</td>
</tr>
<tr>
<td>1990</td>
<td>IEEE 802.11 starts, Announcement of WLAN products</td>
</tr>
<tr>
<td>1991</td>
<td>RAM Mobile (Mobitex)</td>
</tr>
<tr>
<td>1992</td>
<td>Formation of Winforum, ETSI’s HIPERLAN in Europe</td>
</tr>
<tr>
<td>1993</td>
<td>Release of 2.4, 5.2 and 17.1-17.3 GHz bands in EU</td>
</tr>
<tr>
<td>1993</td>
<td>PCS licensed and unlicensed bands</td>
</tr>
<tr>
<td>1993</td>
<td>CDPD - (IBM and 9 operating companies)</td>
</tr>
<tr>
<td>1997</td>
<td>IEEE 802.11 finalized</td>
</tr>
<tr>
<td>2000</td>
<td>General packet radio service (GPRS)</td>
</tr>
<tr>
<td>2002</td>
<td>Wireless PANs and EDGE, CDMA Data</td>
</tr>
<tr>
<td>2007</td>
<td>HSDPA and 3G Data services</td>
</tr>
<tr>
<td>2012</td>
<td>Wimax and LTE</td>
</tr>
</tbody>
</table>
Generic Architecture - WWANs

Visitor Database (ViD)
Home Database (HoD)
Authentication Center (AuC)
Operation & Maintenance Center (OMC)
Equipment Register (ER)

Mobile Switching Center (MSC)
Radio Network Controller (RNC)
Point of Access
Mobile Station

The Internet or PSTN
2G Cellular Network Architecture

BTS - Base Transceiver Subsystem
BSC - Base Station Controller
MSC - Mobile Switching Center
CO - Central Office
VLR - Visitor Location Register
SS 7 - Signaling System 7
Terms and terminology

- **Mobile Station (MS)**
  

- **Point of Access**
  
  - Base Station (BS), Base Transceiver Subsystem (BTS), Mobile Data Base Station (MDBS), Access Point (AP), Node B, E-Node B

- **Radio Controller**
  
  - Base Station Controller – BSC, Radio Network Controller – RNC

- **Mobile Control Center**
  

- **Visiting Database**
  

- **Home Database**
  
  - Home Location Register – HLR, Mobile Home Function – MHF, GPRS Register – GR, Home Agent - HA

Not all elements from the generic architecture exist in all technologies & the exact functionality of the elements may be different.
Functionality (I)

- **Point of access**
  - The physical radio transceiver
  - Creates the air interface
    - Transmits signals to MSs
    - Receives signals from MSs
    - Involved in multiplexing on the link – medium access

- **Radio Network Controller**
  - Again link level
  - Manages the air interface
    - Which RF carrier should I tune to?
    - What transmit power level should I use?
    - Is the carrier I want to use capable of providing acceptable quality?
    - When should I make a handoff?
Base Stations (BS)

- Provides radio channels between mobile units and network
- Pico-cells: (indoor – 0-.5 Km) support 8-20 channels
- Micro-cells: (outdoor – 0-1 Km), Macro-cells: (1-30 Km)
Base Stations and Radio Network Controllers

- **Base Transceiver Subsystem (BTS)**
  - Houses radio units

- **Base Station Controller (BSC)**
  - Manages a cluster of BS, channel assignment, handoff, power control, some switching, etc
Functionality (II)

- **Mobile Switching Center**
  - Manages mobility of devices
    - Routes packets to and from MSs
  - Keeps track of the location of the MSs
    - Location means “in which cell or group of cells” the MS may be located i.e., which points of access may be probable candidates for pinging the MS
    - How does it do this? Using the home database and visiting database
  - Ensures security
    - Uses the authentication center and equipment registers to authenticate the MS and to prevent fraudulent/stolen devices from using the network
- **Accounting and Billing**
  - Operations and maintenance center
Mobile Switching Center (MSC) (MTSO)

- Provides switching functions, coordinates location tracking, call delivery, handoff, interfaces to HLR, VLR, AUC, etc.
- Size of central office switch
Home and Visitor Databases

- **Home Location Register (HLR)**
  - Specialized database server contains billing info, service profile and general location of a mobile user

- **Visitor Location Register (VLR)**
  - Similar to HLR contains location of users and their service profile of all users in a metro type area
Wireless Local Area Networks

- Used primarily in smaller areas
  - Homes, campuses, coffee shops, businesses
  - Support communication to mobile data users via wireless channel

- Standards
  - IEEE 802.11 a, b, g, n standard (wireless Ethernet)
    - 1Mbps, 2Mbps, 11Mbps, 54 Mbps, >100 Mbps rates
      - Use Barker codes, CCK, OFDM, MIMO
    - Infrastructure based and Ad-Hoc based networks
  - HIPERLAN 1 and 2

- Typically use unlicensed spectrum
Generic Architecture - WLANs

- AP-1
- AP-2
- AP-3
- MS-1
- MS-2
- MS-3
- Authentication Server
- LAN segment (distribution system)
- The Internet
- Router
- Basic Service Set (BSS)
- Extended Service Set (ESS)
Ad hoc network topology

- Distributed topology
  - Devices communicate between each other directly (like walkie-talkies)

- Characteristics
  - Reconfigurable networks
  - No need for a wired infrastructure
  - Suitable for rapid deployment

- Need to “discover” communicating parties, services, methods of routing data, and so on
Ad Hoc WLANs

- **MSs communicate in a peer-to-peer manner**
  - Single-hop: They have to be in range of one another
    - Most vendors support only this option
  - Multi-hop: MSs can act as “relay nodes”
    - HIPERLAN/1 supports this, but there are no real products

Independent Basic Service Set (IBSS) in 802.11 WLANs
Ad-hoc topology

Bluetooth: A “cell” or “piconet” is defined by a Master device
- The master controls the frequency hopping sequence
- The master also controls the transmission within its piconet

Others
- Sensor networks, RF-IDs, mobile ad hoc networks
PHY Layer Issues

- The radio channel is harsh
  - Cables and wires have “predictable” and time-invariant transmission characteristics
  - The radio channel is dynamic and harsh
  - Examples of problems
    - Fading
    - Multipath dispersion
    - Signal attenuation due to rain or snow
    - Interference (again!)

- Physical layer issues
  - Coverage
  - Harshness of the radio channel
    - High error rates need mitigation
    - Effect on protocols

- Spectrum Regulation
  - The medium of transmission is air
  - The medium cannot be duplicated and it must be shared by ALL applications
    - Communications, broadcast, emergency services, television, military, etc.
    - Sharing is achieved by allocating separate “bands” of spectrum to users of different applications
      - Broadcast radio: 520-1605.5 kHz – AM Radio
      - Broadcast radio: 87.5 – 108 MHz – FM Radio
    - A band of spectrum refers to a range of electromagnetic frequencies
  - The FCC regulates the spectrum allocated to vendors
MAC layer Issues + Network Design & Deployment

- There is LIMITED spectrum for different applications
- The frequency bands are not “contained” as in the case of wired transmissions
  - There is some interference between signals transmitted in one frequency band and another
  - Same thing is true if you choose to split the band for an application (think AM)
- Capacity is limited and we need novel methods to improve capacity

SUMMARY
- Spectrum and hence bandwidth is limited
- Radio transmissions can cause interference

- MAC layer issues
  - Shared “broadcast” medium
    - Need for a simple decentralized medium access mechanism
  - Performance
    - Throughput, delay and QoS
- Network design and deployment
  - No single type of wireless access is available everywhere
  - Spectrum is scarce
    - Coexistence, interference, planning
  - Frequency reuse and cellular topology
Multiple Access Techniques

- **Orthogonal waveforms**
  - Frequency division multiple access (FDMA)
    - Separate users in frequency
    - Analog 1G systems – AMPS, NMT, TACS etc.
  - Time division multiple access (TDMA)
    - Separate users in time
    - Digital 2G systems – IS-136 and GSM

- **Random (pseudo) and orthogonal waveforms**
  - Code division multiple access (CDMA)
    - Separate users in “code”
    - Digital 2G system – IS-95
    - All 3G systems – IMT-2000 (W-CDMA and cdma2000)

- **Long term evolution (LTE) uses OFDMA**
Radio Resource Management

- Resource limitations
  - Radio resources
  - Power:
    - A mobile device does not have a constant power supply and relies on battery
    - Transmissions consume energy!
      - The battery must last as long as possible before being charged
      - The transmission scheme MUST be efficient in terms of energy consumption

- Radio resource and power management
  - Assignment of radio channels and transmit power
  - Admission control, power control and handoff decision
Mobility Management

- Wireless devices are popular because they do not need to be tethered to a place like wired devices
- Wireless devices are continuously changing locations
  - The connectivity changes
  - Devices may move out of coverage of a service
  - Someone should keep track of where the device is to deliver information to it
  - Someone should make sure that the connection is not broken as a wireless device moves

- In wired communications the “address” of the device identifies its location – this is no longer true with wireless devices
- A moving device will “see” a harsher channel!

- Mobility management
  - Location management
    - Tracking where a MS is
  - Handoff management
    - Routing calls/packets as a MS moves
  - Routing in ad hoc networks
  - Database issues
Operations and Security

- Management and Security
  - Mobile end host is no longer confined to the home network
  - Wireless links can be easily “tapped”
  - Fraud
  - Accounting and billing
  - Conflicts with other issues

- Network operations and management
  - Accounting and billing to charge subscribers correctly
  - Access to resources and services on the network

- Service discovery and data management
  - Sensors and RF-IDs
    - How is data maintained?
    - Where should data reside?
    - How can it be efficiently accessed?
Mobile Device

- Form factor and capabilities
  - A mobile device has to be light weight, durable, have long battery life and yet be capable of performing complex tasks
  - Energy efficient design of software and protocols

- Usability
  - User characteristics (size, dexterity, knowledge, etc.)
  - Environment characteristics (temperature, degree of mobility, etc.)
  - Device Characteristics
    - Start up time
    - Data integrity and security
    - cpu speed and memory size
    - Power supply
    - User interface (keypad, stylus, voice)
Spectrum is scarce

- We need to squeeze as many data bits as possible in a given bandwidth
- The more data bits you squeeze in the more stringent are the system requirements
  - Example: Squeezing in more data => larger signal to noise ratio requirement => larger transmit power => lower battery life
  - Example: multipath dispersion is not a problem at low data rates
  - Example: complex processing can result in large form factor
Summary - II

- Physical layer makes wireless communications unreliable and erroneous
  - Contributes greatly to the complexity of the system
  - Impacts all other aspects of a wireless system
- Fundamentally different from wired networks
  - Resource issues
  - Mobility issues
  - Design issues