

# Technical challenges of wireless communications

## A Simplified Wireless Communications System Representation



## The major challenges

- Multipath propagation
- Spectrum limitations
- Limited energy (battery)
- User mobility

## **Multipath propagation**



## Small-scale fading



## Large-scale fading



## **Consequences of fading**

- Error probability is dominated by probability of being in a fading dip
- Error probability decreases only linearly with increasing SNR interference limited e.g., a probalistic environment as compared to a noise limited environment
- Fighting the effects of fading becomes essential for wireless transceiver design
- Deterministic modeling of channel at each point very difficult
- Statistical modeling of propagation and system behavior

## Intersymbol interference (1)

• Channel impulse response is delay-dispersive (delay spread)



Multipath components with different runtimes

Channel impulse response

## Intersymbol interference (2)



## Signal Energies in a 3D Environment



The capture area represents the direct energy received from the signal source located at the center of the sphere. The direct energy is the signal from the source that is not reflected nor it is scattered, as if the source were in deep space or free space. It might help to view the capture area as the energy at a receiver.

The sphere's surface area  $(A_s)$  increases by a power of 2 as:

 $A_{\rm S} = 4 \ \pi \ r^2$ 

Given the constant energy from the source radiates equally in all directions (uniform energy density over the entire surface area of the sphere), the energy in the capture area is reduced by the inverse square of the distance. This is the basis of the inverse square path loss model - you double the distance from the source and the energy decreases by a 1/4. This is also called the free space path loss model which along with other path loss models will be discussed in Chapters 3, 4 and 7.

The scattered energy density is uniform so as the radius of the sphere r gets larger, the number of scatterers involved in the reflections (multipath) **increases** and the delay spread (the time it takes for the scattered energy to eventually make it to the capture area) also increases. Compared to the direct energy, the scattered energy arriving later at the capture area (the receiver) is the cause of intersymbol interference.

## Spectrum assignment (VHF/UHF/Microwave)

- <100 MHz: CB radio, pagers, and analogue cordless phones. short wave radio, AM broadcast radio, amateur radio
- 100-800 MHz: broadcast (FM radio and TV)
- 400-500 MHz: cellular and trunking radio systems
- 800-1000 MHz: cellular systems (analogue and secondgeneration digital); emergency communications
- 1.8-2.0 GHz: main frequency band for cellular and cordless
- 2.4-2.5 GHz: cordless phones, wireless LANs and wireless PANs (personal area networks); other devices, e.g., microwave ovens.
- 3.3-3.8 GHz: fixed wireless access systems
- 4.8-5.8 GHz: wireless LANs
- 11-15 GHz: satellite TV

## **Frequency reuse**

- Available spectrum is limited resource (like clean air, water)
- Thus the same frequency (range) has to be used at many different locations by many different sources
- Regulated spectrum: Licensed spectrum
  - a single operator owns the spectrum and can determine where to put TXs as allowed by the FCC in the USA normally for a fee
  - cell planning so that interference adheres to certain limits
- Unregulated spectrum: Unlicensed spectrum
  - Often only one type of service allowed, although sharing is allowed
  - Nobody can control location of interferers
  - Power of interferers is limited by regulations and thus idealistically interference is not allowed

## **Duplexing and multiple access**

• Within each frequency band, multiple users need to communicate with one BS (multiple access)



• Cellphones have to be able to transmit and receive voice communications (duplexing) talk and listen at the same time

as compared to simplex where users can only talk one at a time and say something like 'over' to pass control back to the other user

## DUPLEX Frequency-division Duplex (FDD)

Single user FDD diagramed



FDD requires a complex solution (the duplex filter or duplexer).

FDD can be used for continuous transmission.

Examples: Global System for Mobile communications (GSM), Wideband CDMA (WCDMA)

## DUPLEX Time-division duplex (TDD)

Single user TDD is diagramed



Examples: Global System for Mobile communications (GSM), Wideband CDMA (WCDMA) same examples as FDD

## MULTIPLE ACCESS Frequency-division multiple access (FDMA)



Multi users are diagramed

Users are separated in frequency bands.

Examples: Nordic Mobile Telephony (NMT), Advanced Mobile Phone System (AMPS)

## **FDMA**

(Frequency Division Multiple Access)

### Frequency





## **FDMA Channel Allocation**







## Frequency Hopping (Chapter 18 - Spread Spectrum)



## MULTIPLE ACCESS Time-division multiple access (TDMA)



## **TDMA** (Time Division Multiple Access)



## **TDMA Frame Structure**



## **TDMA Frame Illustration for Multiple Users**



## MULTIPLE ACCESS Carrier-sense multiple access (CSMA)



## **MULTIPLE ACCESS** Code-division multiple access (CDMA)



Users are separated by spreading codes.

\* codes of a very special mathematical nature - orthogonal

Examples: CdmaOne, Wideband CDMA (WCDMA), Cdma2000

## CDMA (Code Division Multiple Access)



## Transmitted and Received Signals in a CDMA System



## **User mobility**

- User can change position
- Mobility within one cell (i.e., maintaining a link to a certain BS)
  Biggest impact on channel propagation fading
- Mobility from cell to cell: various techniques used to manage moving a cell customer from one cell to another adjacent cell while maintaining the connection



Illustration of a cell with a mobile station and a base station

## **Cellular System Infrastructure**



#### Early wireless system: Large zone

1st Generation of Cell System which was an analog system

## **Cellular System: Small Zones**



## Cellular Network Organization

- Use multiple low-power transmitters (Base Stations of a 100 W or less; 1G cell phones under 5 watts, 3G/4G smart phones in mW)
- Overall coverage area divided into cells
  - Each cell served by its own antenna system (switched directional antennas)
  - Each cell is served by base station consisting of transmitter, receiver and control unit, the base stations are connected to a MTSO (see cellular system overview slide)
  - Band of frequencies allocated, duplex communication channels used in a cellular/voice system
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)


#### Impact of Cell Shape and Radius on Service Characteristics

Shape of the Cell	Area	Boundary	Boundary Length/ Unit Area	Channels/ Unit Area with N Channels/ Cell	Channels/Unit Area when Number of Channels is Increased by a Factor K	Channels/Unit Area when Size of Cell Reduced by a Factor M
Square cell (side =R)	R <sup>2</sup>	4R	$\frac{4}{R}$	$\frac{N}{R^2}$	$\frac{\mathrm{KN}}{R^2}$	$\frac{M^2N}{R^2}$
Hexagonal cell (side=R)	$\frac{3\sqrt{3}}{2}R^2$	6R	$\frac{4}{\sqrt{3}R}$	$\frac{\mathrm{N}}{1.5\sqrt{3}R^2}$	$\frac{\mathrm{KN}}{1.5\sqrt{3}R^2}$	$\frac{\mathrm{M}^2\mathrm{N}}{1.5\sqrt{3}R^2}$
Circular cell (radius=R)	$\pi R^2$	2πR	$\frac{2}{R}$	$\frac{N}{\pi R^2}$	$\frac{\mathrm{KN}}{\pi R^2}$	$\frac{M^2N}{\pi R^2}$
Triangular cell (side=R)	$\frac{\sqrt{3}}{4}R^2$	3R	$\frac{4\sqrt{3}}{R}$	$\frac{4\sqrt{3}N}{3R^2}$	$\frac{4\sqrt{3}\mathrm{KN}}{3R^2}$	$\frac{4\sqrt{3}M^2N}{3R^2}$



## **Actual Signal Strength**



tiling. This happens because of terrain, presence of obstacles and signal attenuation in the atmosphere.

# Cell Pattern (hexagonal)



## Frequency Reuse

- Adjacent cells assigned different frequencies to avoid interference to each other, also called crosstalk
- Objective is to reuse frequency in non-adjacent cells (hidden transmitter phenomena)
  - Multiple frequencies assigned to each cell (10 to 50 frequencies)
  - Transmission power controlled (ALE) at both ends to limit interference between cells using the same frequencies
  - The <u>issue</u> is to determine how many cells must intervene between two cells (reuse distance) that will be using the same frequencies to avoid co-channel interferrence
  - # of cells in a repetitious pattern where the cells in the pattern use a unique/non-repeating set of frequencies Reuse Factor N which must satisfy  $N = i^2 + ij + j^2$

# Frequency Reuse Patterns



(a) Frequency reuse pattern for N = 4



(b) Frequency reuse pattern for N = 7



(c) Black cells indicate a frequency reuse for N = 19

#### Cells, N Reuse Factor, Clusters → Design Constraints

- N Cells which <u>collectively</u> use the same set of available frequencies are a **Cluster** (none of the cells within a cluster use the same frequency)
- The i and j terms will indicate where the next co-channel cell is located (cells that use the same frequencies)
- Larger N → less co-channel interference as the ratio of the cell radius to distance between co-channel cells decreases. A smaller N indicates co-channel cells are much closer together
- As the number of Clusters is replicated within a system, then the total system capacity is increased
- Overall design is to allocate the total available bandwidth for each cluster (which will be replicated to comprise the total system) and divide up the cluster bandwidth amongst the N reuse factor to determine the number of channels per cell. The co-channel interference will dictate the size of N. The details of Co-Channel Interference will be covered in Chapter 17 -Multiple Access but it is dependent on distance and signal power

## **Frequency Reuse**



7 cell reuse cluster

## **Reuse Distance**



• For hexagonal cells, the reuse distance is given by

 $D = \sqrt{3NR}$ 

where *R* is cell radius and *N* is the reuse factor (the cluster size or the number of cells per cluster).

#### **Co-Channel Cell Locations**

-The cluster size or the number of cells per cluster is given by

 $N = i^2 + ij + j^2$  For i = 3, j = 2 then N = 19 which is the reuse factor or the number of cells per cluster.



**Figure 3.2** Method of locating co-channel cells in a cellular system. In this example, N = 19 (i.e., i = 3, j = 2). (Adapted from [Oet83] © IEEE.)

## Approaches to Increasing Capacity

- Adding new channels (have a reserve avaiable)
- Frequency borrowing frequencies are taken from adjacent cells by congested cells
- Cell splitting cells in areas of high usage can be split into smaller cells (more cell equipment per system → \$\$)
- Cell sectoring cells are divided into a number of wedgeshaped sectors each with their own set of channels using a base station with highly directional antennas (120°/60°)
- Microcells cells become much smaller and antennas move to buildings, hills and lamp posts but still controlled by a single site. Reduced power levels required in the microcells (zone cells) to prevent co-channel interference



#### **Cell Splitting Power Reduction - Example**

For new split cells with **a** radius **half** that of the original cells **R --> R/2** 

at old cell boundary received power  $P_r \propto P_{t1} R^{-\gamma}$ at new cell boundary received power  $P_r \propto P_{t2} (R/2)^{-\gamma}$ 

 $\gamma$  = propagation path loss varies between 2 (inverse square) and 5 If we take  $\gamma = 4$  and set the received powers equal to each other then  $P_{t2} = P_{t1} / 16$  In logarithmic terms since  $dB = 10 \log(1/16) = -12.04$  then  $P_{t2}db = P_{t1}dB - 12.04$ The transmit power for the new split cells must be reduced by 12.04 dB and would be even greater for the free space (inverse square) path loss model where  $\gamma = 2$ 



## **Cell Sectoring by Antenna Design**

Placing directional transmitters at corners where three adjacent cells meet



## Cellular System Implementation



## MS, BS, BSC, MSC (MTSO) and PSTN



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## Cellular Systems Terms

- Base Station (BS) includes an antenna system, a controller and a number of receivers
- Mobile telecommunications switching office (MTSO) – connects calls between mobile units
- Two types of channels available between mobile unit and BS, channels further divided into forward and reverse for duplex communications
  - Control channels used to exchange information having to do with setting up and maintaining calls
  - Traffic channels carry voice or data connection between users

### **Control and Traffic Channels**



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## Steps in an MTSO Controlled Call between Mobile Users

- Mobile unit initialization (select strongest base station)
- Mobile-originated call (request for a connection)
- Paging (sent from MTSO to other BSs or data base query + verify)
- Call accepted (+ billing)
- Ongoing call
- Handoff (switching base stations when required)

#### Additional Functions in an MTSO Controlled Call

- Call blocking (BS busy, busy signal sent)
- Call termination (releases traffic channels)
- Dropped Call (loss of signal strength)
- Calls to/from fixed and remote mobile subscribers (use of public switched telephone network – POTS)

## Mobile Radio Propagation Effects

- Signal strength (UHF & microwave frequencies)
  - Must be strong enough between base station and mobile unit to maintain signal quality at the receiver (SNR)
  - Must not be so strong as to create excessive cochannel interference with channels in another cell using the same frequency band. Adaptive control of power very key to system.
- Fading
  - Signal propagation effects may disrupt the signal and cause errors
  - Wireless RF environment extremely tough. Operational aspects don't help either (small omni-directional antennas in handsets, users move around → handoffs, low-power, non-optimum/urban locations)



Maintaining the telephone number across geographical areas in a wireless and mobile system

#### Handoffs - Performance Metrics for Decision

- Cell blocking probability probability of a new call being blocked
- Call dropping probability probability that a call is terminated due to a handoff
- Call completion probability probability that an admitted call is not dropped before it terminates
- Probability of unsuccessful handoff probability that a handoff is executed while the reception conditions are inadequate

#### Handoff Performance Metrics (cont)

- Handoff blocking probability probability that a handoff cannot be successfully completed
- Handoff probability probability that a handoff occurs before call termination
- Rate of handoff number of handoffs per unit time
- Interruption duration duration of time during a handoff in which a mobile is not connected to either base station
- Handoff delay distance the mobile moves from the point at which the handoff should occur to the point at which it does occur

## Various Handoff Strategies Used to Determine Instant of Handoff

- Relative signal strength
- Relative signal strength with threshold
- Relative signal strength with hysteresis (prevent 'oscillating' handoffs)
- Relative signal strength with hysteresis and threshold
- Prediction techniques



**Distance** *x* **of MS from BS** 

# Handoff Region



By looking at the variation of signal strength from either base station it is possible to decide on the optimum area where handoff can take place

## Power Control

- Design issues make it desirable to include dynamic power control in a cellular system
  - Received power must be sufficiently above the background noise for effective communication
  - Desirable to minimize power in the mobile station (MS) transmitted signal
    - Reduce cochannel interference, alleviate health concerns, save battery power
    - Dynamic transmitter power control becoming mandatory in almost all modern RF communications systems
  - In spread spectrum systems using CDMA, it's necessary to equalize the received power level from all mobile units at the BS so as to maximize # of users (N = 1 in CDMA) with a usable SNR for all the 'customers' in each cell

## Types of Power Control

- Open-loop power control
  - Depends solely on mobile unit (monitor Base Station pilot signal)
  - No feedback from BS
  - Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
- Closed-loop power control
  - Adjusts signal strength in the reverse channel based on performance metrics
  - BS makes power adjustment decision and communicates to mobile on control channel to set the user's cell phone power level

## History: First-Generation Analog

- Advanced Mobile Phone Service (AMPS)
  - In North America, two 25-MHz bands allocated to AMPS
    - One for transmission from base to mobile unit
    - One for transmission from mobile unit to base
  - Each band split in two to encourage competition
  - Frequency reuse exploited

# **AMPS** Operation

- Subscriber initiates call by keying in phone number and presses send key
- MTSO verifies number and authorizes user
- MTSO issues message to user's cell phone indicating send and receive traffic channels
- MTSO sends ringing signal to called party
- Party answers; MTSO establishes circuit and initiates billing information
- Either party hangs up; MTSO releases circuit, frees channels, completes billing

#### Differences Between First (1G) and Second Generation (2G) Systems

- Digital traffic channels first-generation systems are almost purely analog; second-generation systems are digital (circuit switched)
- Encryption all second generation systems provide encryption to prevent eavesdropping
- Error detection and correction second-generation digital traffic allows for detection and correction, giving clear voice reception
- Channel access second-generation systems allow channels to be *dynamically* shared by a number of users (TDMA or CDMA)

#### Mobile Wireless TDMA Design Generic Requirements

- Number of logical channels (number of time slots in TDMA frame): 8 (min req for multiplexing considerations)
- Maximum cell radius (R): 35 km (for traffic levels)
- Frequency: region around 900 MHz (allocated)
- Maximum vehicle speed  $(V_m)$ : 250 km/hr (for trains)
- Maximum coding delay: approx. 20 ms (max delay for voice conversations based on propagation distance)
- Maximum delay spread ( $\Delta_m$ ): 10 µs (max multipath)
- Bandwidth: Not to exceed 200 kHz (25 kHz per channel; typical channel bandwidth)





System Design Constraints

Figure 10.12 Steps in Design of TDMA Timeslot

# TDMA Transmission Time Slot



0.5 ms

(b) Approximate field sizes
### Global System for Mobile Communications (GSM) Network Architecture (2<sup>nd</sup> Generation, started in Europe)



Generic handsets until SIM card is inserted

#### Figure 10.14 Overall GSM Architecture

# Mobile Station

- Mobile station communicates across Um interface (air interface) with base station transceiver in same cell as mobile unit
- Mobile equipment (ME) physical terminal, such as a telephone or PCS
  - ME includes radio transceiver, digital signal processors and subscriber identity module (SIM)
- GSM subscriber units are generic until SIM is inserted (smart card)
  - SIMs roam, not necessarily the subscriber devices

# Base Station Subsystem (BSS)

- BSS consists of base station controller and one or more base transceiver stations (BTS)
- Each BTS defines a single cell
  - Includes radio antenna, radio transceiver and a link to a base station controller (BSC)
- BSC reserves radio frequencies, manages handoff of mobile unit from one cell to another within BSS and controls paging

# Network Subsystem (NS)

- NS provides link between cellular network and public switched telecommunications networks
  - Controls handoffs between cells in different BSSs
  - Authenticates users and validates accounts
  - Enables worldwide roaming of mobile users
  - User/Equipment Databases
- Central element of NS is the mobile switching center (MSC/MTSO)

## Mobile Switching Center (MSC/MTSO) Databases

- Home location register (HLR) database stores information about each subscriber that belongs
- Visitor location register (VLR) database maintains information about subscribers currently physically in the region
- Authentication center database (AuC) used for authentication activities, holds encryption keys
- Equipment identity register database (EIR) keeps track of the type of equipment that exists at the mobile station

## CDMA Cellular – 2<sup>nd</sup> Generation System

- Direct-sequence spread spectrum (DSSS)
- Frequency diversity frequency-dependent transmission impairments (e.g. fading) have less effect on signal which is spread over a large bandwidth
- Multipath resistance chipping codes used for CDMA exhibit low cross correlation and low autocorrelation
- Privacy privacy is inherent. For DSSS, each user has a unique code resulting in spread spectrum/noise-like signals
- Graceful degradation system only gradually degrades (SNR) as more users access the system

# Drawbacks of CDMA Cellular

- Self-jamming arriving transmissions from multiple users are not aligned on chip boundaries unless the users are perfectly synchronized, requires very accurate timing sources (GPS receiver/discipline clock)
- Near-far problem signals closer to the receiver are received with less attenuation than signals farther away and given lack of complete orthogonality, distant stations more difficult to recover – power control very important
- Soft handoff requires that the mobile acquires the new cell before it relinquishes the old; this is more complex than hard handoff used in FDMA and TDMA schemes

### Mobile Wireless CDMA Design Considerations

- RAKE receiver when multiple versions of a signal (multipath very common) arrive more than one chip interval apart, RAKE receiver attempts to recover signals from these multiple paths and combine them for performance
  - This method achieves better performance than simply recovering dominant signal and treating remaining signals as noise
- Soft Handoff mobile station is temporarily connected to more than one base station simultaneously, switching center selects best base station



### Figure 10.18 Principle of RAKE Receiver [PRAS98]

# Third-Generation Capabilities (3G)

- Voice quality comparable to the public switched telephone network
- 144 kbps data rate available to users in high-speed motor vehicles over large areas
- 384 kbps available to pedestrians standing or moving slowly over small areas
- Support for 2.048 Mbps for office use
- Symmetrical / asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services
- First 3G wireless system: 1x EV-DO (CDMA high data rate)

# 3G Capabilities (continued)

- An adaptive interface to the Internet to efficiently utilize the asymmetry between the inbound and outbound traffic
- More efficient use of the available spectrum in general
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies (video, text messaging, wireless VOIP, GPS services, etc.)