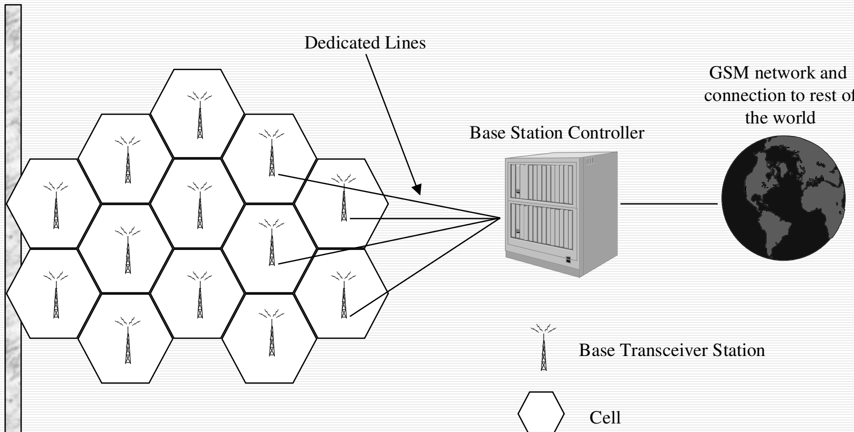
Course Overview

- Introduction and History
- Regulatory Issues
- Fundamentals of Cellular Systems
- 1st Generation: AMPS and CDPD
- 2nd Generation: GSM
- 3rd Generation: IMT-2000
- Mobile IP
- TCP over Wireless Link

Physical View of Cellular Networks



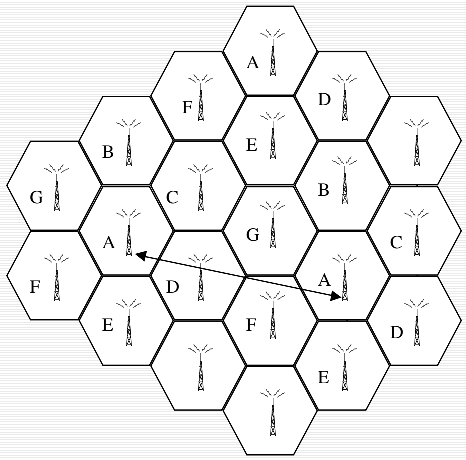
Radiowave Propagation

- transmission over wireless link (from mobile to base station controller) unreliable:
  - severe attenuation and shadowing, approximately r^{-4}
    - inverse-square law only in vacuum
    - on ground: buildings/walls, foliage, etc.
  - distortions due to multipath propagation
    - transmission reflected from objects
    - same signal arrives at receiver at different times, resulting composite signal either stronger or weaker
    - effects differ for different frequencies and user mobility

Radiowave Propagation

- errors are not independent, typically a burst of errors is followed by an error-free period
- case study: error behavior for WaveLAN transmissions (Nguyen, Katz, Noble, Satayanarayanan):
  - WaveLAN: commercial wireless network interface in the 902 - 908 MHz ISM band (AT&T)
  - maximum bandwidth of 2 Mbps
  - errors measured and analyzed when sending UDP packets
  - results:
    - higher transmission rates do not lead to an increase in errors
    - packet error rate increases exponentially with packet size
    - packet error rate increases exponentially with distance
    - two-state Markov Mode not a good description of error behavior: length distributions for each state are not geometric

Frequency Reuse



A - G: frequency groups
Idea: group cells into clusters and do not reuse same frequency within cluster

↔ reuse distance D
D = R*sqrt(3N)
R = cell radius
N = reuse pattern (7 in example)

Reuse patterns:
-groups of 7 cells
-groups of 3 cells

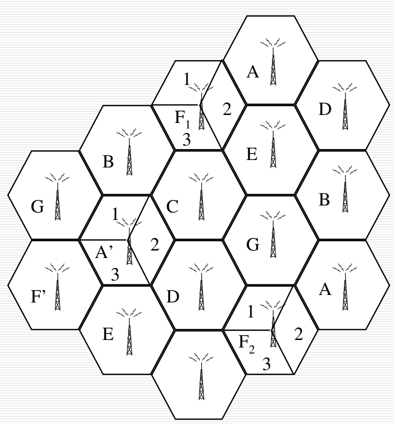
Cell Size and Capacity

- cell size determines number of cells available to cover geographic area and (with frequency reuse) the total capacity available to all users
- capacity within cell limited by available bandwidth and operational requirements
- so each network operator has to size cells to handle expected traffic demand

Increasing Cellular System Capacity

- cell splitting
  - decrease transmission power in base and mobile
  - results in more and smaller cells
  - reuse frequencies in non-contiguous cell groups
  - example: 1/2 cell radius leads 4-fold capacity increase
- cell sectoring
  - directional antennas subdivide cell into 3 or 6 sectors
  - might also increase cell capacity by factor of 3 or 6
  - idea: borrow frequencies from neighbor
  - use borrowed frequencies in a controlled fashion, not in part of cell adjacent to lending cell

Cell Sectoring



Cell A' is "hotspot", needs more capacity
Cell F' has spare capacity, is "donor"
Cell A' uses frequencies X
Cell A' borrows frequencies Y from F'
Cell F' has frequencies Z remaining
Cells F_1 and F_2 also use frequencies Z and Y

Problem: how to keep reuse of frequencies Y at reasonable distance?

Solution: subdivide cells into sectors
- Cell A' uses borrowed frequencies Y in sector 1
- Cell F_1 uses remaining frequencies Z in sector 3, both sets of frequencies in other sectors
- Cell F_2 uses remaining frequencies Z in sector 1, both sets of frequencies in other sectors

Channel Utilization Schemes

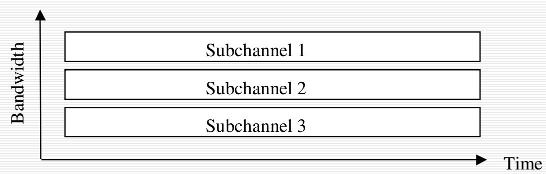
- communications channel is valuable resource
- problem: how to utilize resource efficiently
- compression
  - sharing the channel with multiple users (maybe)
  - intended to utilize overloaded channel more effectively
- multiplexing
  - sharing the channel with multiple users (definitely)
  - designed to use underloaded channel more effectively

Multiplexing (Overview)

- Frequency Division Multiplexing (FDM)
  - Frequency Division Duplex (FDD)
  - Time Division Duplex (TDD)
- Time Division Multiplexing (TDM)
- Code Division Multiple Access (CDMA)
  - Frequency Hopping
  - Direct Sequence

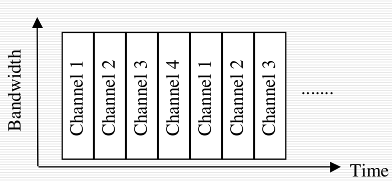
Frequency Division Multiplexing (FDM)

- idea: divide transmission frequency range into narrower bands (subchannels)
- used widely in telephone, microwave, CATV, satellite
  - frequency division duplex: use two subchannels for communication, one for uplink, one for downlink (AMPS)
  - time division duplex: use same subchannel for both directions, take turns

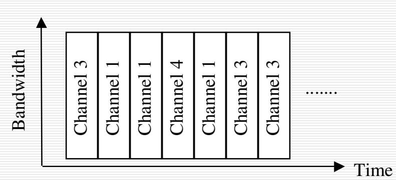


Time Division Multiplexing (TDM)

- TDM gives user access to full channel capacity, but only for limited time periods, rotating channel among all users
- pure TDM wastes bandwidth because stations might not use slots, therefore allocate time slots dynamically



Pure Time Division Multiplexing



Statistical Time Division Multiplexing

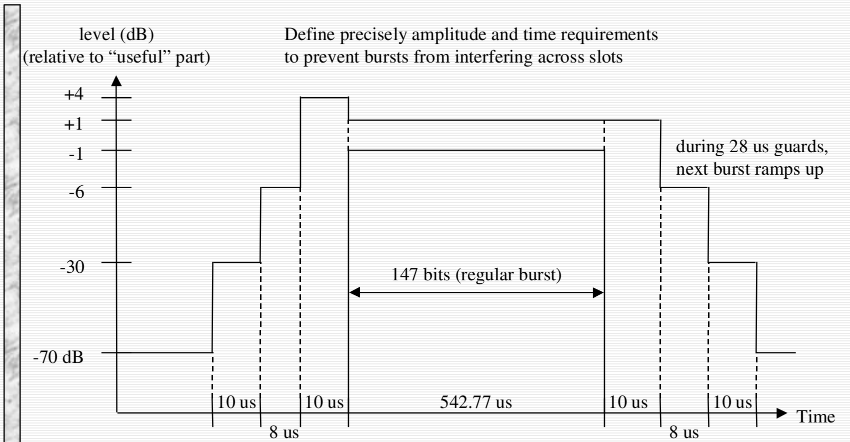
Combining FDM and TDM

- GSM combines FDM and TDM: bandwidth is subdivided into channels of 200 kHz, shared by up to eight stations, assigning slots for transmission on demand

etc.	Burst 1	Burst 2	Burst 3	Burst 4	Burst 5	Burst 6	Burst 7	Burst 8
200 kHz	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms
200 kHz	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms
200 kHz	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms
200 kHz	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms	0.577 ms

....

GSM: Burst Details



Code Division Multiple Access (CDMA)

- use whole frequency band to transmit data, everyone can transmit simultaneously
- separate multiple transmissions appropriately
- cocktail party analogy: how do numerous pairs of people in a room interact
  - TDM: all people in room center, taking turns talking
  - FDM: people spread around room in clusters, conversations within clusters simultaneously
  - CDMA: all people in room center, talking at the same time, but in different languages

CDMA: Frequency Hopping

- originally developed to foil jamming by military opponent
- idea: divide frequency band into subbands, transmit data in one subband at each instant, but change frequency subband frequently
- frequency changes pseudo-randomly to thwart attacker (or to reduce collision likelihood with parallel send attempt)
- sender and receiver need to agree on sequence of frequency changes

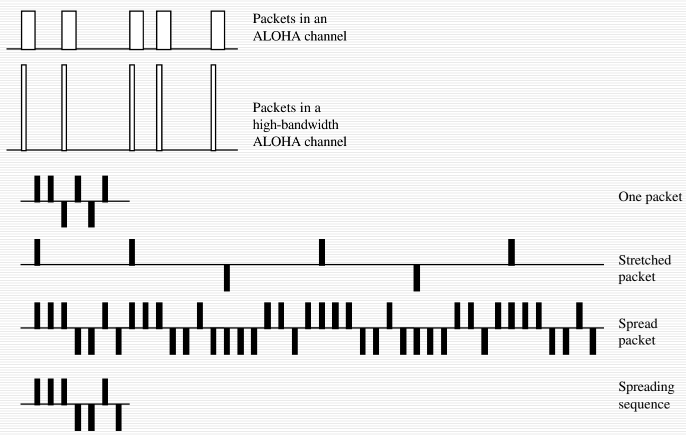
CDMA: Frequency Hopping

- How to deal with collisions?
  - voice transfer: loss of small amounts of information not critical, just drop it (but: QoS!)
  - data transfer: have to ensure that no data is lost
    - hopping sequences within one cell orthogonal, so only interference possible with transmissions in a neighbor cell
    - transmissions from other cells low in power, typically treated as noise and filtered out
    - channel coding and interleaving of data ensure that receiver can tolerate a certain number of burst errors. In GSM, interleaving is done over 8 bursts, and approximately two of these 8 bursts can get wiped out and recovered at receiver

CDMA: Direct Sequence

- subdivide each individual bit into m signals (chips) and transmit those using full bandwidth
- each station is assigned a unique m-bit code or chip sequence, which is combined with value of data bit to determine sending sequence (for a bit value of 1, send chip sequence, for a bit value of 0 send one’s complement)
- receiving station reconstructs data bit from m samples, tolerates certain amount of interference
- effect is that b bits/second of information are spread out over mb chips/second, form of spread spectrum communication, operational requirement for ISM bands

CDMA: Direct Sequence



CDMA: Direct Sequence Example

- Why does direct sequence CDMA work? Answer: chip sequences are orthogonal
- example:
  - use bipolar notation: binary 0 is -1, binary 1 is +1
  - let **S** denote chip sequence for station S, $\overline{\mathbf{S}}$ its negotiation
  - orthogonality: inner product of two chip sequences **S** and **T** (**S** **T**) is 0:

$$S \bullet T \equiv \frac{1}{m} \sum_{i=1}^{m} S_i T_i = 0$$

CDMA: Direct Sequence Example

- orthogonality requirement: “as many pairs are the same as are different” in each chip sequence
- it also follows that

$$S \bullet \overline{T} \equiv \frac{1}{m}\sum_{i=1}^{m} S_i \overline{T}_i = 0$$

$$S \bullet S \equiv \frac{1}{m}\sum_{i=1}^{m} S_i S_i = 1$$

$$S \bullet \overline{S} \equiv \frac{1}{m}\sum_{i=1}^{m} S_i \overline{S}_i = -1$$

CDMA: Direct Sequence Example

Assume four stations A, B, C, and D, with chip sequences as listed below:

A: 0 0 0 1 1 0 1 1 or in bipolar notation $(-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$
B: 0 0 1 0 1 1 1 0 or in bipolar notation $(-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$
C: 0 1 0 1 1 1 0 0 or in bipolar notation $(-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$
D: 0 1 0 0 0 0 1 0 or in bipolar notation $(-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$

Also, assume that signals from multiple senders add up linearly. Below are six scenarios, showing the result of one ore more stations transmitting a bit simultaneously. Remember that for each bit, depending on its value, either the whole chip sequence or the complement of the chip sequence is sent:

Station A	Station B	Station C	Station D
---	---	1	---
---	1	1	---
1	0	---	---
1	0	1	---
1	1	1	1
1	1	0	1

S1 $= (-1 + 1 - 1 + 1 + 1 + 1 - 1 - 1)$
S2 $= (-2\ \ 0\ \ 0\ \ 0 + 2 + 2\ \ 0 - 2)$
S3 $= (\ \ 0\ \ 0 - 2 + 2\ \ 0 - 2\ \ 0 + 2)$
S4 $= (-1 + 1 - 3 + 3 + 1 - 1 - 1 + 1)$
S5 $= (-4\ \ 0 - 2\ \ 0 + 2\ \ 0 + 2 - 2)$
S6 $= (-2 - 2\ \ 0 - 2\ \ 0 - 2 + 4\ \ 0)$

CDMA: Direct Sequence Example

Station A	Station B	Station C	Station D
---	---	1	---
---	1	1	---
1	0	---	---
1	0	1	---
1	1	1	1
1	1	0	1

$\mathbf{S1} = (-1 + 1 - 1 + 1 + 1 + 1 - 1 - 1)$
$\mathbf{S2} = (-2\ \ 0\ \ 0\ \ 0 + 2 + 2\ \ 0 - 2)$
$\mathbf{S3} = (\ \ 0\ \ 0 - 2 + 2\ \ 0 - 2\ \ 0 + 2)$
$\mathbf{S4} = (-1 + 1 - 3 + 3 + 1 - 1 - 1 + 1)$
$\mathbf{S5} = (-4\ \ 0 - 2\ \ 0 + 2\ \ 0 + 2 - 2)$
$\mathbf{S6} = (-2 - 2\ \ 0 - 2\ \ 0 - 2 + 4\ \ 0)$

Just as a reminder:
C = $(-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

To recover the signal sent by a transmitter, receiver needs to know the chip sequence of sender. If received chip sequence is **S** and receiver tries to listen to station with chip sequence **C**, just calculate the inner product:

$\mathbf{S1} \bullet C = (1+1+1+1+1+1+1+1)/8 = 1$
$\mathbf{S2} \bullet C = (2+0+0+0+2+2+0+2)/8 = 1$
$\mathbf{S3} \bullet C = (0+0+2+2+0-2+0-2)/8 = 0$
$\mathbf{S4} \bullet C = (1+1+3+3+1-1+1-1)/8 = 1$
$\mathbf{S5} \bullet C = (4+0+2+0+2+0-2+2)/8 = 1$
$\mathbf{S6} \bullet C = (2-2+0-2+0-2-4+0)/8\ = -1$

CDMA: Direct Sequence Example

Why does this work? Because of the way the chip sequences are picked. In the third scenario, for example, A and C send a bit value of 1 while B sends a bit value of 0. The receiver sees the sum

$$S = A + \overline{B} + C$$

and calculates:

$$S \bullet C = (A + \overline{B} + C) \bullet C =$$
$$A \bullet C + \overline{B} \bullet C + C \bullet C =$$
$$0 + 0 + 1 = 1$$

The first two (interfering) terms vanish because the chip sequences have been chosen carefully, e.g., they are orthogonal.

CDMA: Direct Sequence

- in an ideal, noiseless channel, the capacity (i.e., the number of stations) can be made arbitrarily large
- however, having all chip sequences synchronized in time is impossible
  - receiver has to synchronize with sender by having sender send long enough known chip sequence that receiver can lock into
  - all other (unsynchronized) transmissions will appear as random noise, requiring larger chip sequences
- implicit assumption so far was that power level of all senders are same as perceived by receiver
  - in mobile environment, power of received signal depends on distance between mobile and base station
  - requires power management (typically by base station)

CDMA: Direct Sequence (DS) vs. Frequency Hopping (FH)

- FH has potentially less total interference:
  - ratio of intracell-to-intercell interference is two to one
  - no intracell interference in FH case
- no power control necessary to ensure all signals are received at base with equal strength
- external jamming potentially handled more gracefully by FH
- DS requires contiguous wide band, FH spectrum does not have to be contiguous
- FH has somewhat more complex radio control

Comparison of Multiple Access Techniques

- TDM: common radio and modem equipment, at a given carrier frequency, can be shared among N users at base station
- TDM can adopt dynamically to user traffic demands (statistical TDM), compared to FDM
- TDM has less stringent power control requirements than DS CDMA
- time slot structure gives time for measurements of alternative slots, frequencies, etc. in order to support mobile assisted or mobile controlled handoff (will be discussed when talking about GSM in more detail)

Comparison of Multiple Access Techniques

- TDM has more complex RF units
  - time slots become available periodically
  - power envelope is therefore periodically pulsating
- TDM requires complex timeslot assignment and management (again, will become somewhat clearer when discussing GSM)
- TDM is more susceptible to errors due to multipath fading than FDM (higher bandwidth)

Comparison of Multiple Access Techniques

Operation	AMPS (FDM)	TDMA	CDMA
Bandwidth	12.5 MHz	12.5 MHz	12.5 MHz
Frequency Reuse	k = 7	k = 7	k = 1
RF channel	0.03 MHz	0.03 MHz	1.25 MHz
Number of RF channel	12.5/0.03 = 416	12.5/0.03 = 416	12.5/1.25 = 10
Channels per cell	416/7 = 59	416/7 = 59	12.5/1.25 = 10
Usable channels/cell	57	57	10
Calls per RF channel	1	3	38
Voice channels/cell	57 x 1 = 57	57 x 3 = 171	10 x 38 = 380
Sectors/cell	3	3	3
Voice calls/cell	57/3 = 19	171/3 = 57	380
Capacity vs. AMPS	---	3x	20x

Note: this is just one possible comparison, many researchers would agree that objective comparisons are difficult to make since it is almost impossible to have similar assumptions for different systems and different system features. E.g.: capacity is a "soft" number for CDMA systems (can always be increased at the cost of some performance), but is a "hard" number for other systems.