Course Overview

- Introduction and History
- Data in Wireless Cellular Systems
- Data in Wireless Local Area Networks
- Internet Protocols
- Routing and Ad-Hoc Networks
- TCP over Wireless Link
- Services and Service Discovery
- System Support for Mobile Applications

Regulatory Issues

- Wireless Spectrum scarce, shared among many different users with distinct needs
- Need either license to operate in specific frequency band or use unlicensed frequency band
- Unlicensed bands: no limit on number of users, but rules governing “behavior”
- Licenses used to be given away basically for free, but this became controversial, plus governments saw this as easy source of revenue…..
- Need for international standardization: meetings every 2 years (WARC), many international standards bodies and regulatory offices involved

FCC Allocations

- FCC: Federal Communications Commission
  - allocates frequencies in less than 10 GHz range
  - US agency, but relevant to Canada (Industry Canada keeps spectrum allocation “compatible with that adopted by the United States”)
  - allocations determine which bands to use and whether to operate in a licensed or unlicensed band
  - unlicensed bands: can be used subject to operational procedures
  - licensed bands: high performance, expensive

Unlicensed Bands

- Industrial, Scientific, and Medical (ISM):
  - 915 MHz band (902 - 928 MHz, 26 MHz bandwidth)
    - only available in North America
    - highly crowded, expected to become even more crowded
    - many existing users are non-spread-spectrum applications
  - 2.4 GHz band (2.4 - 2.4835 GHz, 83.5 MHz bandwidth)
    - available worldwide
    - lightly loaded, but interference from microwave ovens
  - 5.8 GHz band (5.725 - 5.85 GHz, 125 MHz bandwidth)
    - only available in North America
    - lightly loaded, radar interference

Unlicensed Band

- Personal Communications Services (PCS):
  - 1.9 GHz band (1910 - 1930 MHz, 20 MHz bandwidth)
    - part of overall PCS band (1850-1990 MHz)
    - 1910-1920: unlicensed asynchronous or packet-switched applications
    - 1920-1930: unlicensed synchronous or circuit-switched applications
    - open band in Europe around 1.9 GHz for digital enhanced cellular telephone (DECT)
    - in US, this band currently occupied by other users with microwave point-to-point links, who will clear the band in a few years

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Licensing 3G Bands

Source: *http://www.umts-forum.org/brochures/3G_licensing_09_October.pdf*

- VERY different country rules:
  - **US**: finalise spectrum options by Q3 2001, prior to licensing 3G systems by Q4 2002. consultation process completed 30 March 2001 with reports from FCC and NTIA.
  - **Canada** auctioned PCS spectrum in January 2001 that can be used for 3G services, with 52 licences attracting bids totalling $1.48 billion.
  - Spectrum policy in USA and Canada is today not service specific. This means that any licensee can deploy 3G systems in their existing spectrum, if equipment exists for that particular spectrum.
  - **France:** 4 National licenses, beauty contest plus fixed cost. First two licences awarded to Itineris (France Telecom) and SFR (Cegetel). Conditions have yet to be set for the award of two further licences. First licences awarded 31.05.01. Date of second call for tender not yet confirmed
  - **Germany:** 6 National licences awarded, five 2x10 + 5 MHz, one 2x10 MHz. 1st stage auction completed (17.8.00), raising DM98.8 billion. Second stage closed 18.8.00, awarding an additional 1x5Mhz unpaired to all except one.

Channel Utilization Schemes

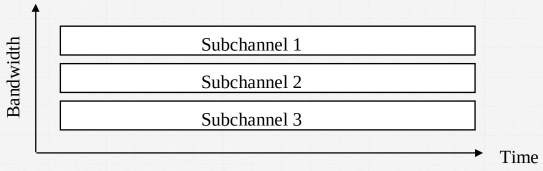
- communications channel is valuable resource
- problem: how to utilize resource efficiently
- compression
  - sharing the channel with multiple users (maybe)
  - intended to utilize overloaded channel more effectively
- multiplexing
  - sharing the channel with multiple users (definitely)
  - designed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

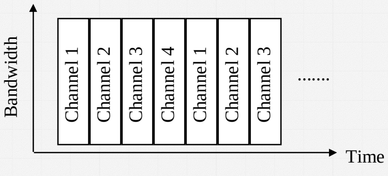
Frequency Division Multiplexing (FDM)

- 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

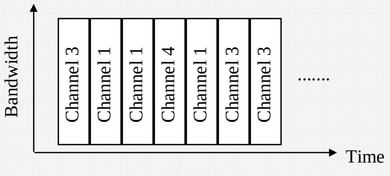


Time Division Multiplexing (TDM)

- 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

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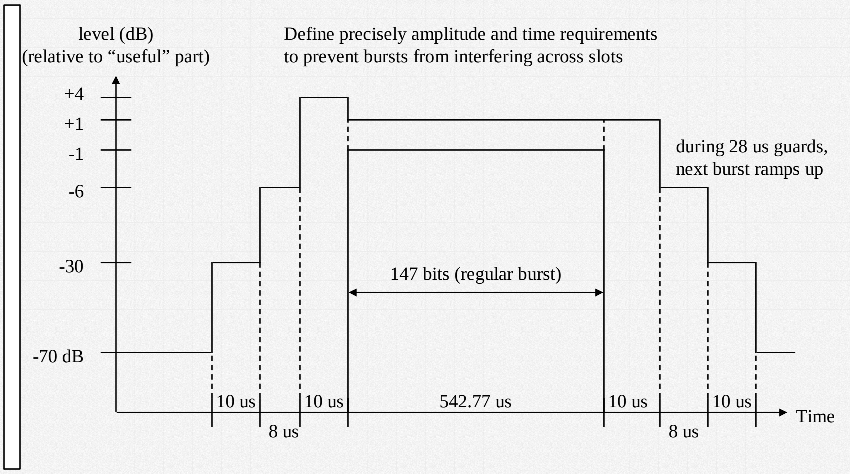
GSM: Burst Details

Define precisely amplitude and time requirements
to prevent bursts from interfering across slots



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

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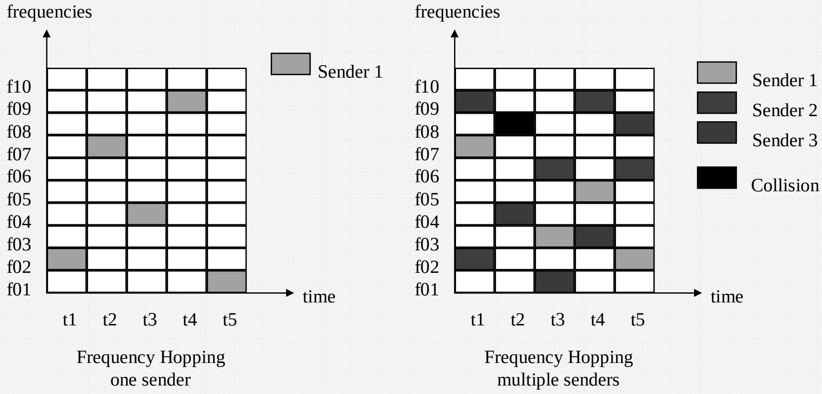
CDMA: Frequency Hopping

- 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



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

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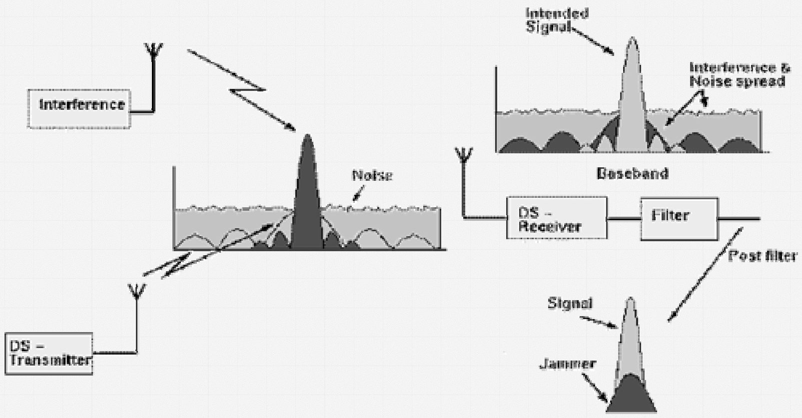
CDMA: Direct Sequence



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

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

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:

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

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/sector	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.