Wireless Communication Fundamentals

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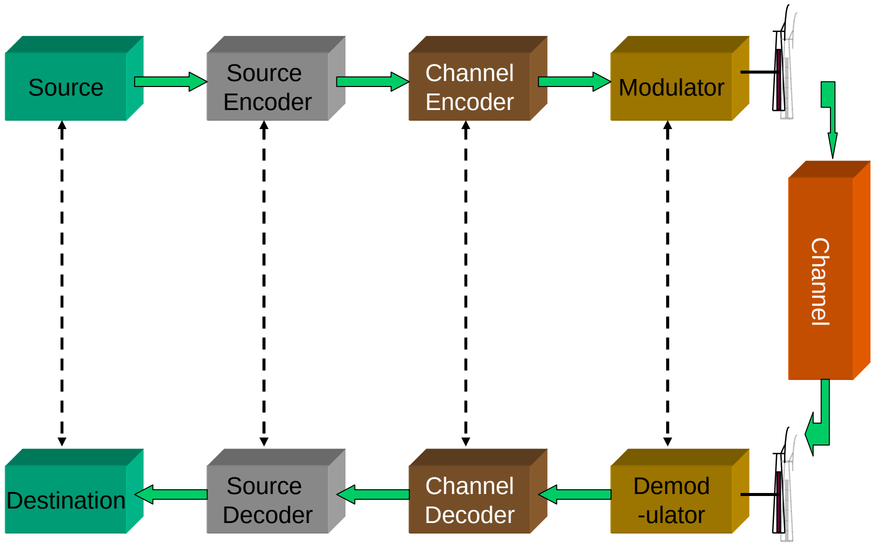
Typical Wireless Communication System



Source
Source Encoder
Channel Encoder
Modulator
Channel
Demod -ulator
Channel Decoder
Source Decoder
Destination

The Radio Channel

- Three main issues in radio channel
  - **Achievable signal coverage**
    - What is geographic area covered by the signal
    - Governed by path loss
  - **Achievable channel rates (bps)**
    - Governed by multipath delay spread
  - **Channel fluctuations – effect data rate**
    - Governed by Doppler spread and multipath

What is Diversity?

- Idea: Send the same information over several "uncorrelated" forms
  - Not all repetitions will be lost in a fade
- Types of diversity
  - **Time diversity** – repeat information in time spaced so as to not simultaneously have fading
    - Error control coding!
  - **Frequency diversity** – repeat information in frequency channels that are spaced apart
    - Frequency hopping spread spectrum,OFDM
  - **Space diversity** – use multiple antennas spaced sufficiently apart so that the signals arriving at these antennas are not correlated
    - Usually deployed in all base stations but harder at the mobile

Performance Degradation and Diversity

Issue	Performance Affected	Diversity Technique
Shadow Fading	Received Signal Strength	Fade Margin – Increase transmit power or decrease cell size
Fast Fading	Bit error rate Packet error rate	Antenna Diversity Error control coding Interleaving Frequency hopping
Multipath Delay Spread	Inter-symbol Interference	Adaptive Equalization DS-Spread Spectrum OFDM Directional Antennas

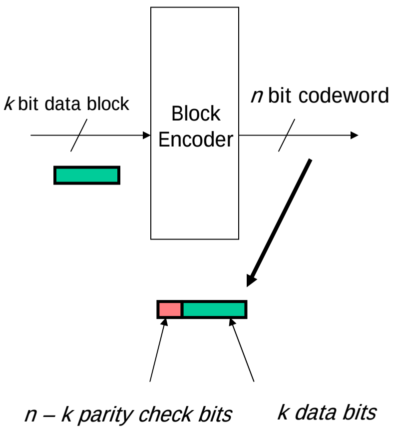
Error Control

- BER in wireless networks
  - Several orders of magnitude worse than wireline networks (eg, 10^{-2} vs 10^{-10} in optic fibers)
  - Channel errors are random and bursty, usually coinciding with deep fast fades
  - Much higher BER within bursts
- Protection against bit errors
  - Necessary for data
  - Speech can tolerate much higher bit errors ($< 10^{-2}$ depending on encoding/compression algorithm)
- Error Control Coding used to overcome BER

Error control coding

- Coding is a form of diversity
  - Transmit redundant bits from which you can detect/recover from errors
  - The redundant bits have a pattern that enables this recovery
- Approaches to error control
  - Error Detection + ARQ
  - Error Correction (FEC)

Simple Block code



Error control

- Error control coding: systematically add *redundant* bits for error detection or correction
  - Error detection codes:
    - Detect whether received word is a valid “codeword” but not enough redundancy to correct bits
    - Retransmit data after error (automatic repeat request –ARQ)
  - Error correction codes (forward error correction: FEC)
    - Detect invalid codewords and correct into valid codeword
    - Correction requires more bits than error detection
    - FEC is good for one-way channels, recordings (CD-ROMs), real-time communications, deep space,...
  - Generally more bits are required to protect against larger number of bit errors

Single Parity

- Example:
- single parity bit --- *even* parity code
  - Valid codewords should always have *even* number of 1’s
  - Add a parity bit=1 if number of 1’s in data is odd add parity bit=0 if number of 1’s in data is even
  - If any bit is in error, the received codeword will have odd number of 1’s
  - Single parity can detect any single bit error (but not correct)
    - Actually, any odd number of bit errors can be detected

Single Parity (cont)

Example

--> 2^3 valid codewords

received codewords

valid	invalid
0000	0001
0011	0010
0101	0100
0110	0111
1001	1000
1010	1011
1100	1101
1111	1110

Single bit error will change valid word into an invalid word (detectable); double bit error will change valid word into another valid word (undetectable)

Block Codes

- (n,k) block codes

  k = number of data bits in block (data word length)

  n-k = number of parity check bits added

  n = length of codeword or code block

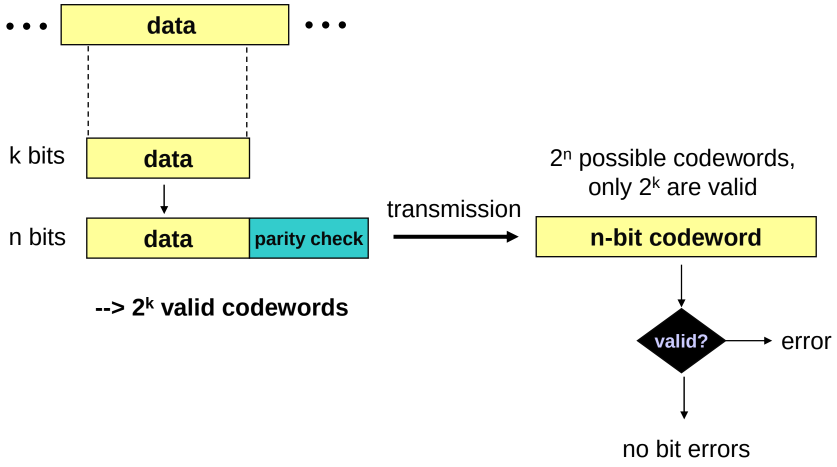
  (n-k)/n = overhead or redundancy

  (lower is more efficient)

  k/n = coding rate

  (higher is more efficient)

Block Codes (cont)



--> 2^k valid codewords

Block Code Principles

- Hamming distance :
  - for 2 *n*-bit binary sequences, the number of different bits
  - e.g., $v_1=011011;\ \ v_2=110001;\ \ d(v1, v_2)=3$
- The minimum distance (d_{min}) of an (n,k) block code is the smallest Hamming distance between any pair of codewords in a code.
  - Number of error bits can be detected: d_{min}-1
  - Number of error bits can be corrected t:

$$t = \left\lfloor \frac{d_{\min} - 1}{2} \right\rfloor$$

(7,4) Hamming code

Message word	Code word	Weight
0000	000 0000	0
0001	101 0001	3
0010	111 0010	4
0011	010 0011	3
0100	011 0100	3
0101	110 0101	4
0110	100 0110	3
0111	001 0111	4
1000	110 1000	3
1001	011 1001	4
1010	001 1010	3
1011	100 1011	4
1100	101 1100	4
1101	000 1101	3
1110	010 1110	4
1111	111 1111	7

2^7 possible 7-bit words (128 possible) of which we use only 16

All codewords are distance 3 apart => Can detect 2 errors, correct 1 error

Forward Error Correction Process

FEC Operation

- Transmitter
  - –Forward error correction (FEC) encoder maps each k-bit block into an n-bit block codeword
  - –Codeword is transmitted;
- Receiver
  - –Incoming signal is demodulated
  - –Block passed through an FEC decoder
  - –Decoder detects and correct errors
- Receiver can correct errors by mapping invalid codeword to nearest valid codeword

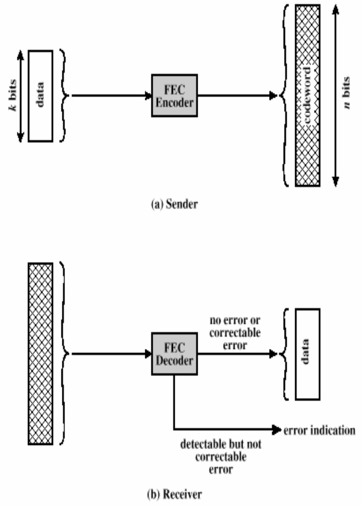
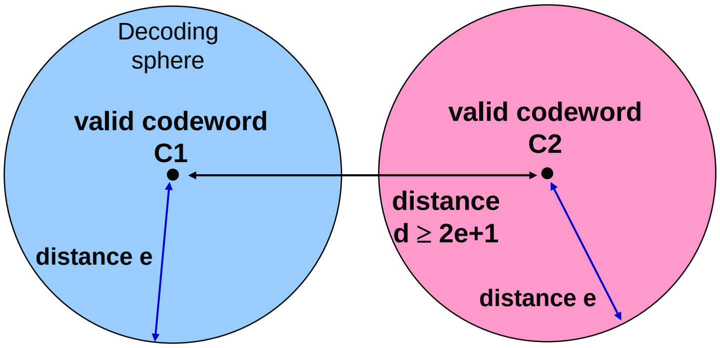


Figure 8.5 Forward Error Correction Process

FEC (cont)



Decoding sphere

valid codeword C1

distance e

valid codeword C2

distance d $\geq$ 2e+1

distance e

Convolutional Codes

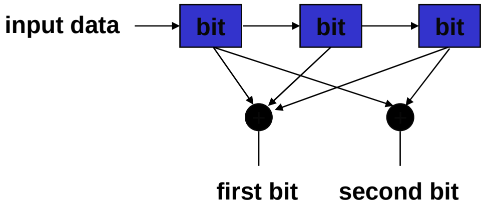
- Block codes treat data as separate blocks (memoryless encoding);
- Convolutional codes map a continuous data string into a continuous encoded string (memory)
- Error checking and correcting carried out continuously
  - (n, k, K) code
    - Input processes k bits at a time
    - Output produces n bits for every k input bits
    - K = constraint factor
    - k and n generally very small
  - n-bit output of (n, k, K) code depends on:
    - Current block of k input bits
    - Previous K-1 blocks of k input bits

Convolutional Codes (cont)

Successive k-tuples are mapped into n-tuples

- n-tuples should be designed to have distance properties for error detection/correction

- Example: K=3 stages, k=1, n=2 bits output



input data

bit

bit

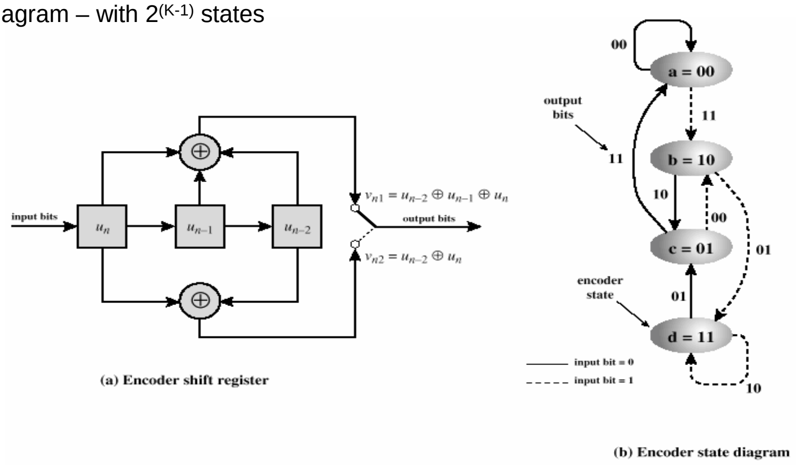
bit

first bit

second bit

Convolutional Encoder

Can represent coder by state transition diagram – with $2^{(K-1)}$ states



(a) Encoder shift register

(b) Encoder state diagram

Figure 8.9 Convolutional Encoder with (n, k, K) = (2, 1, 3)

What does coding get you?

- Consider a wireless link
  - – probability of a bit error = q
  - – probability of correct reception = p
  - – In a block of k bits with no error correction
  - – *P(word correctly received)* = p^k
  - – *P(word error)* = $1 - p^k$
  - – With error correction of t bits in block of n bits

$$P(word\ \ correct\ ) = \sum_{i=0}^{t} \binom{n}{i} (p)^{n-i} q^i$$

$$P(word\ \ error\ ) = 1 - P(word\ \ correct\ )$$

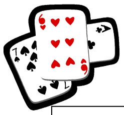
What does coding get you?

- Example consider (7,4) Hamming Code when *BER* = $q = .01,\ p = .99$
  - In a block of *4* bits with no error correction
  - *P(word correctly received)* = $p^k = .9606$
  - *P(word error)* = $1 - p^k = \ 0.04$
  - With error correction of *1* bits in block of *7* bits

$$P(word\ \ correct\ ) = \sum_{i=0}^{t} \binom{n}{i} (p)^{n-i} q^{i} = p^{7} + \binom{7}{6} (p)^{7} q^{1} = 0.998$$

$$P(word\ \ error\ ) = 1 - P(word\ \ correct\ ) = 0.002$$

  - Get an order of magnitude improvement in word error rate

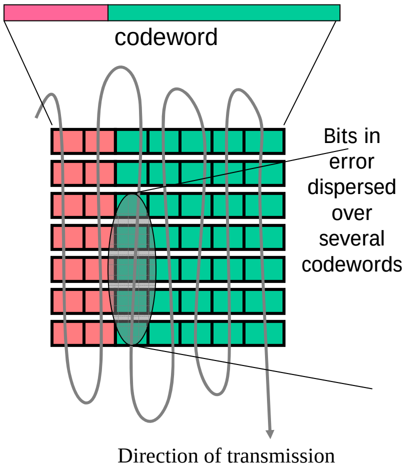


Interleaving

- Problem:
  - Errors in wireless channels occur in *bursts* due to fast fades
  - Error correction codes designed to combat *random errors* in the code words
- Interleaving Idea:
  - If the errors can be spread over many codewords they can be corrected- achieved my shuffling codewords
  - makes the channel memoryless and enables coding schemes to perform in fading channels.
  - the penalty is the delay in receiving information- bits have to be buffered for interleaving
  - Interleaving is performed after coding – at receiver de-interleave before decoding

Block interleaving

- After codewords are created, the bits in the codewords are interleaved and transmitted
- This ensures that a burst of errors will be dispersed over several codewords and not within the same codeword
- Needs buffering at the receiver to create the original data
- The interleaving depth depends on the nature of the channel, the application under consideration, etc.



Interleaving Example

- Usually transmit data in order it arrives

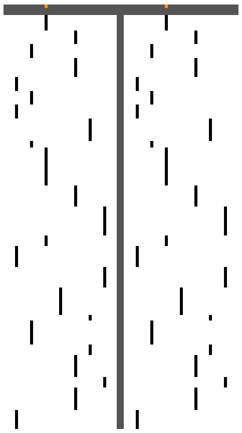
bit position :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
bit :	a_0	a_1	a_2	a_3	a_4	a_5	a_6	b_0	b_1	b_2	b_3	b_4	b_5	b_6	c_0	c_1	c_2	c_3

- Suppose bits 6 to 11 are in error because of a fade ➔ The codewords **a** and **b** are lost.
- Suppose we interleaving at depth 7 by buffering up 7 words then output them in order to bit positions of the words

bit position :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
bit :	a_0	b_0	c_0	d_0	e_0	f_0	g_0	a_1	b_1	c_1	d_1	e_1	f_1	g_1	a_2	b_2	c_2	d_2

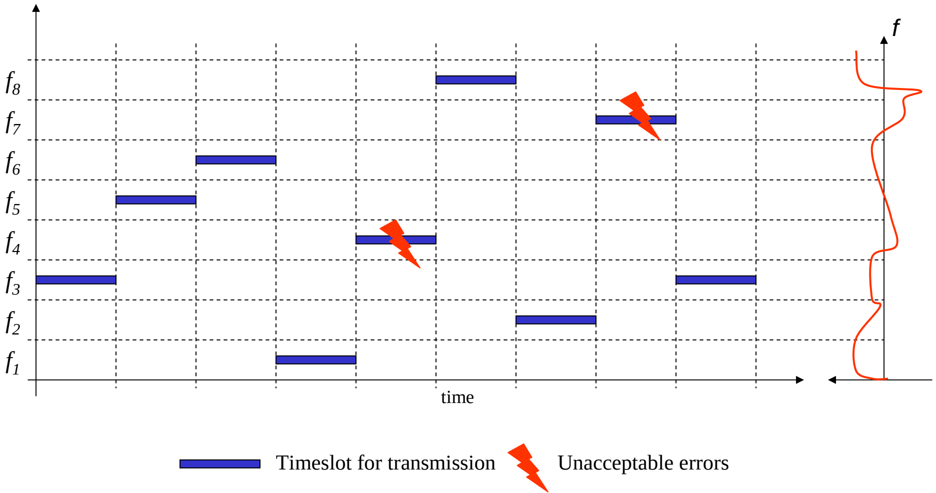
- Now can correct a fade that results in bits 6-11 being lost

Frequency Hopping



- Traditionally: transmitter/receiver pair communicate on fixed frequency channel.
- Frequency Hopping Idea:
  - Since noise, fading and interference change somewhat with frequency band used – move from band to band
  - Time spent on a single frequency is termed the dwell time
- Originally for military communications
  - Spend a short amount of time on different frequency bands to prevent interception or jamming - developed during WWII by actress Hedy Lammar and classical composer George Antheil – patent given to government

Frequency Hopping concept



Frequency Hopping

- Two types:
  - Slow Hopping
    - Dwell time long enough to transmit several bits in a row (timeslot)
  - Fast Hopping
    - Dwell time on the order of a bit or fraction of a bit (primarily for military systems)
- Transmitter and receiver must know hopping pattern/ algorithm before communications.
  - *Cyclic pattern* – best for low number of frequencies and combating Fast Fading :
    - Example with four frequencies: f4, f2, f1, f3, f4, f2, f3, ….
  - Random pattern – best for large number of frequencies, combating co-channel interference, and interference averaging
    - Example with six frequencies: f1, f3, f2, f1, f6, f5, f4, f2, f6, …
    - Use random number generator with same seed and both ends

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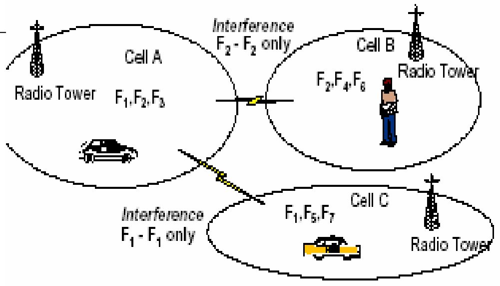
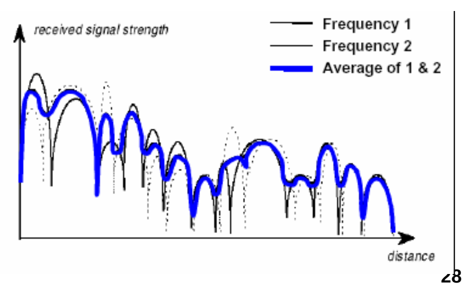
Frequency Hopping

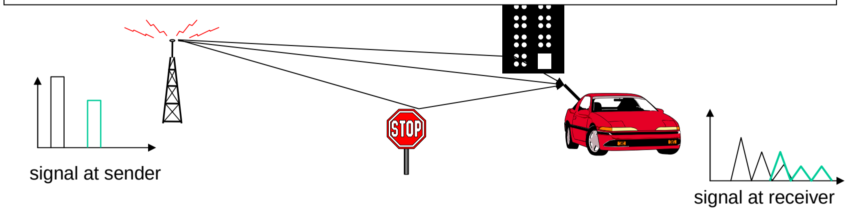
- Slow frequency hopping used in cellular (GSM)
- Fast in WLANs
- Provides interference averaging and frequency diversity
- By hopping mobile less like to suffer consecutive deep fades





Multipath Propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



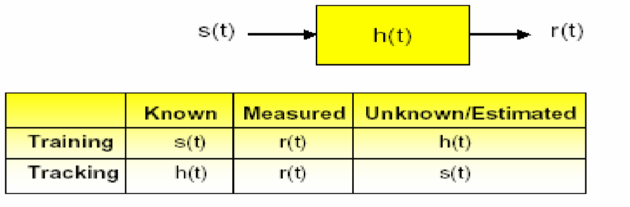
- Time dispersion: signal is dispersed over time
- ➔ interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
- ➔ distorted signal depending on the phases of the different parts

Equalization

- Equalizer
  - filter that performs the inverse of the channel to compensate for the distortion created by multipath delay (combats ISI)
- In wireless networks equalizers must be adaptive
  - channel is usually unknown and time varying
  - equalizers track the time variation and adapt
- Two step approach to equalization
  1. Training**:**
     - a known fixed-length sequence is transmitted for the receiver’s equalizer to ‘train’ on – that is to set parameters in the equalizer
  2. Tracking:
     - the equalizer tracks the channel changes with the help of the training sequence, and uses a channel estimate to compensate for distortions in the unknown sequence.

Adaptive Equalization

- Training step, the channel response, h(t) is estimated
- Tracking step, the input signal, s(t), is estimated



	Known	Measured	Unknown/Estimated
Training	s(t)	r(t)	h(t)
Tracking	h(t)	r(t)	s(t)

- Equalizers are used in NA-TDMA, GSM and HIPERLAN
- There are several different types of equalizers (3 popular ones)
  - LTE: Linear transversal filter
  - DFE: Decision feedback equalizer
  - MLSE: Maximum likelihood sequence estimators
- Disadvantages of equalizers are complexity, bandwidth consumption and power consumption

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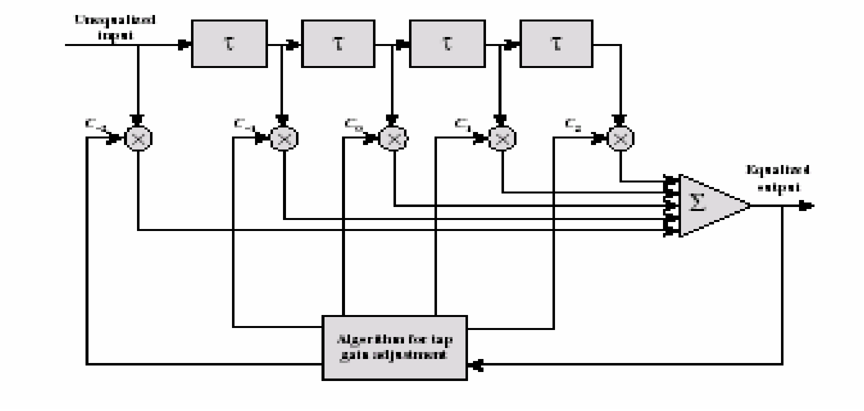
Adaptive Equalizers

Typical equalizer implemented as a tap delay line filter with variable tap gains



Spread Spectrum Radio Aspects

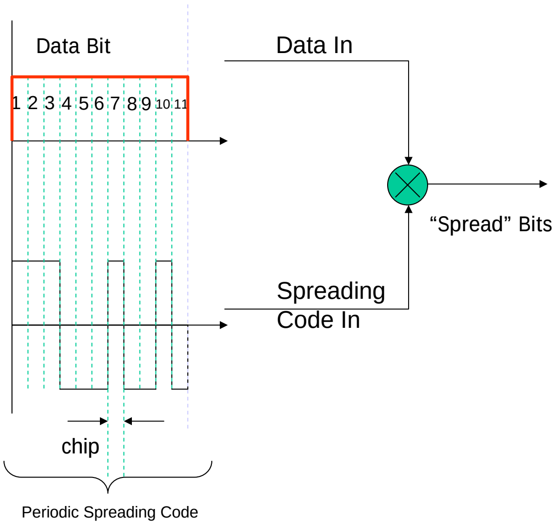
- Military Spread spectrum techniques adapted for cellular systems
  1. Frequency Hopping: vary frequency transmit on
  2. Direct Sequence
     - Narrowband signal is spread over very large bandwidth signal using a spreading signal
     - Spreading signal is a special code sequence with rate much greater than data rate of message
     - The receiver uses correlation to recover the original data
- Multipath fading is reduced by direct sequence signal spreading and better noise immunity
- DS also allows lower power operation – harder to detect and jam

Direct Sequence Spread Spectrum

- Each bit in original signal is represented by multiple bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of chip bits W used
  - Processing gain G = W/R; W = chips per sec, R = information bit rate per sec
  - Processing gain is a measure of the improvement in SNR gained by using the additional bandwidth from spreading (18-23 dB in cellular systems)
- One Spreading technique combines digital information stream with the spreading code bit stream using exclusive-OR

DSSS Modulation

- The original data stream is “chipped” up into a pattern of pulses of smaller duration
- Good **correlation** properties
- Good **cross-correlation** properties with other patterns
- Each pattern is called a spread spectrum code



Data Bit

1 2 3 4 5 6 7 8 9 10 11

Data In

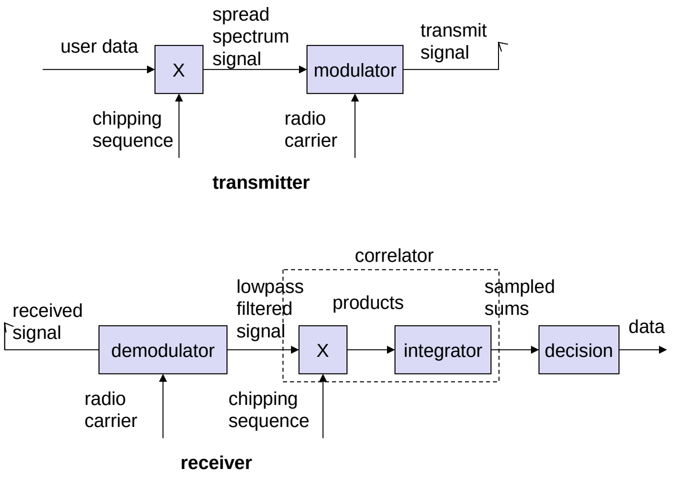
“Spread” Bits

Spreading Code In

chip

Periodic Spreading Code

DSSS (Direct Sequence Spread Spectrum) II



user data

X

spread spectrum signal

modulator

transmit signal

chipping sequence

radio carrier

transmitter

correlator

received signal

demodulator

lowpass filtered signal

X

products

integrator

sampled sums

decision

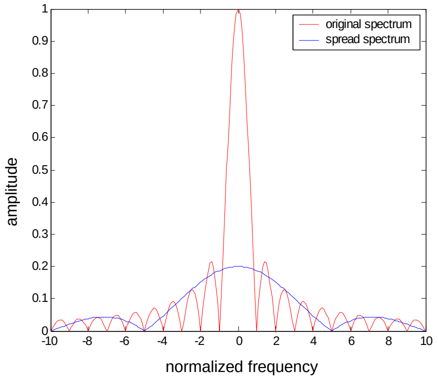
data

radio carrier

chipping sequence

receiver

DSSS Spectrum



spectrum

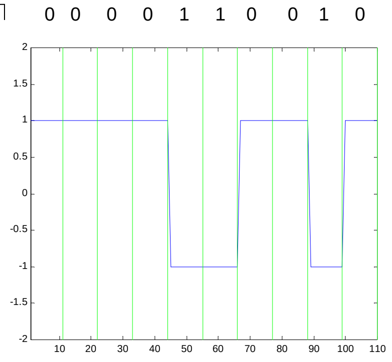
- Example: IEEE 802.11 Wi-Fi Wireless LAN standard

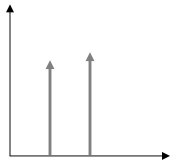
Uses DSSS with 11 bit chipping code

  - To transmit a “0”, you send
    [1 1 1 -1 -1 -1 1 -1 -1 1 -1]
  - To transmit a “1” you send
    [-1 -1 -1 1 1 1 -1 1 1 -1 1]
- Processing gain
  - The duration of a chip is usually represented by T_c
  - The duration of the bit is T
  - The ratio $T/T_c = R$ is called the “processing gain” of the DSSS system
  - For 802.11 R = 11

Example in a two-path channel

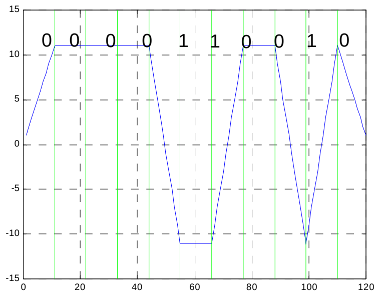
- Random data sequence of ten data bits
  - Spreading by 11 chips using 802.11b chipping code
- Two path channel with inter path delay of 17 chips > bit duration
- Multipath amplitudes
  - Main path: 1
  - Second path: 1.1
- Reality:
  - Many multipath components
  - Different path amplitudes
  - Noise



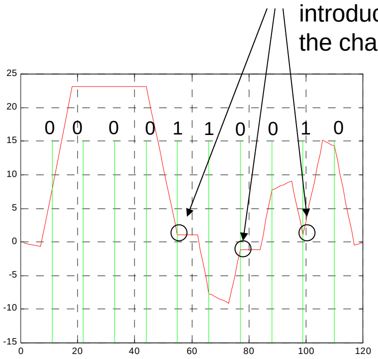


Output without spreading

Errors introduced by the channel



Without Multipath

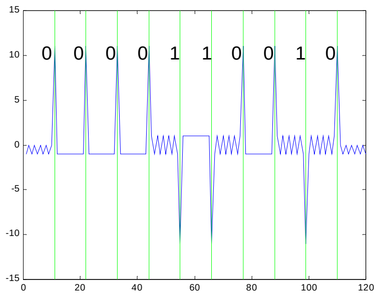


With Multipath

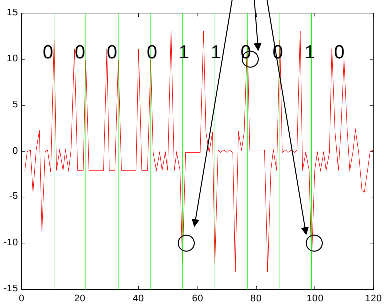
Output with spreading

Errors introduced by the channel are removed

Output of DSS demodulator

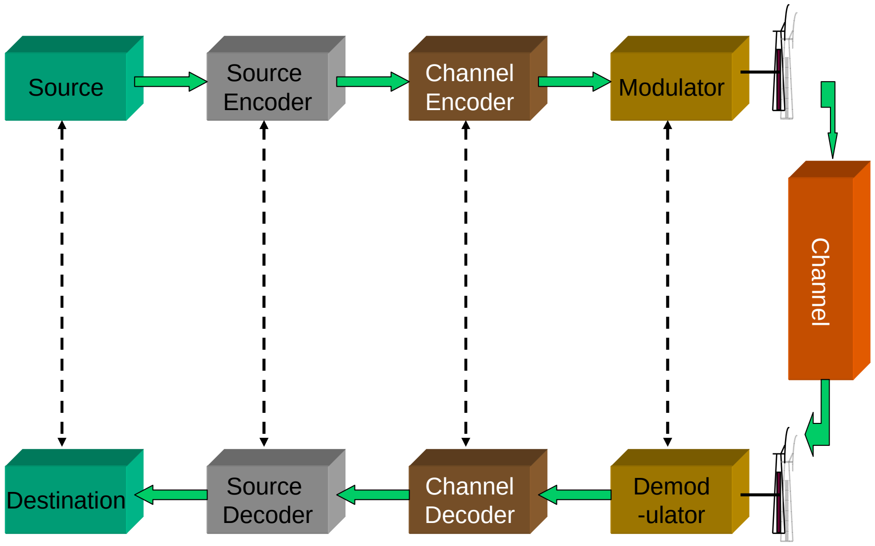


Without Multipath



With Multipath

Typical Wireless Communication System



Source

Source Encoder

Channel Encoder

Modulator

Channel

Destination

Source Decoder

Channel Decoder

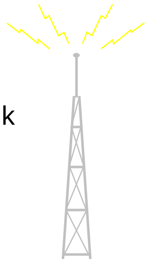
Demod -ulator

Performance Degradation and Diversity

Issue	Performance Affected	Diversity Technique
Shadow Fading	Received Signal Strength	Fade Margin – Increase transmit power or decrease cell size
Fast Fading (Time Variation)	Bit error rate Packet error rate	Antenna Diversity Error control coding Interleaving Frequency hopping
Multipath Delay Spread (Time Dispersion)	Inter-symbol Interference	Adaptive Equalization DS-Spread Spectrum OFDM Directional Antennas

Cell Planning

- **Link Budget**
  - – Used to plan useful radio coverage of cells
    - Relates transmit power, path losses, margins, interference, etc.
    - Used to find max allowable path loss on each link
  - – Typical Factors in Link Budget
    - Transmit Power,
    - Antenna Gain, Diversity Gain,
    - Receiver Sensitivity
    - Shadow Margin, Interference Margin,
    - Vehicle Penetration Loss, Body Loss, Building Penetration, etc..
  - – Gains are added, Losses are subtracted – must balance



Link Budget

Link	Up	Down
TX Power	30dbm	30dbm
Antenna Gain	3	5
Antenna Diversity Gain	5	X
Shadow Margin	10	10
Body Attenuation	2	2
Vehicle Penetration	5	5
Receiver Sensitivity	-105	-90
Path Loss Budget	126 db	108 db

Typical Cellular System Downlink Limited!

Multiple Access and Mode

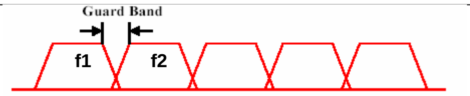
- Mode
  - – Simplex – one way communication (e.g., broadcast AM)
  - – Duplex – two way communication
    - TDD – time division duplex – users take turns on the channel
    - FDD – frequency division duplex – users get two channels – one for each direction of communication
      - – For example one channel for uplink (mobile to base station) another channel for downlink (base station to mobile)
- Multiple Access determines how users in a cell share the frequency spectrum assigned to the cell: FDMA, TDMA, CDMA
- Wireless systems often use a combination of schemes; GSM – FDD/FDMA/TDMA

Multiple Access Techniques

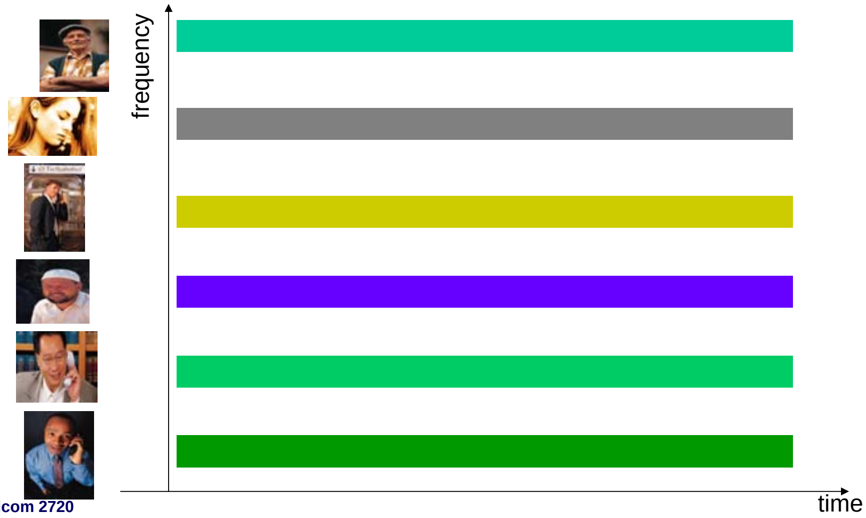
- FDMA (frequency division multiple access)
  - – separate spectrum into non-overlapping frequency bands
  - – assign a certain frequency to a transmission channel between a sender and a receiver
  - – different users share use of the medium by transmitting on non-overlapping frequency bands at the *same time*
- TDMA (time division multiple access):
  - – assign a fixed frequency to a transmission channel between a sender and a receiver for a certain amount of time (users share a frequency channel in time slices)
- CDMA (code division multiple access):
  - – assign a user a unique code for transmission between sender and receiver, users transmit on the same frequency at the same time

FDMA

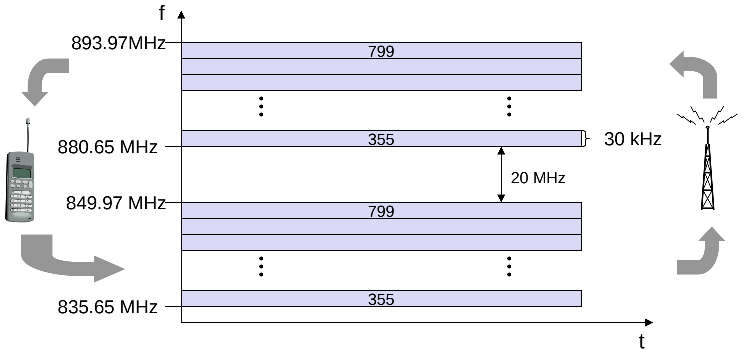
- FDMA is simplest and oldest method
- Bandwidth F is divided into T non-overlapping frequency channels
  - Guard bands minimize interference between channels
  - Each station is assigned a different frequency
- Can be inefficient if more than T stations want to transmit or traffic is bursty (resulting in unused bandwidth and delays)
- Receiver requires high quality filters for adjacent channel rejection
- Used in First Generation Cellular (NMT)



Frequency division multiple access



FDD/FDMA - general scheme, example AMPS (B block)

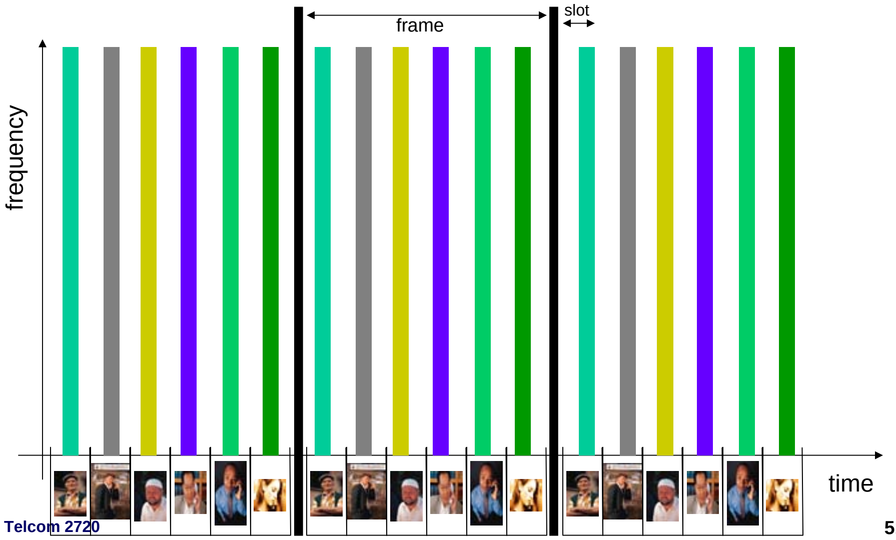


f(c) = 825,000 + 30 x (channel number) KHz <- uplink
f(c) = f uplink + 45,000 KHz <- downlink
In general all systems use some form of FDMA

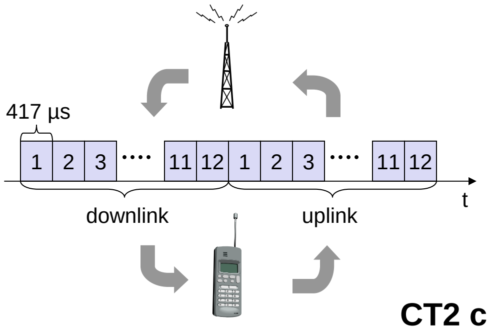
TDMA

- Users share same frequency band in non-overlapping time intervals, eg, by round robin
- Receiver filters are just windows instead of bandpass filters (as in FDMA)
- Guard time can be as small as the synchronization of the network permits
  - All users must be synchronized with base station to within a fraction of guard time
  - Guard time of 30-50 microsec common in TDMA
- Used in GSM, NA-TDMA, (PDC) Pacific Digital Cellular

Time Division Multiple Access



TDD/TDMA - general scheme, example



CT2 cordless phone standard

GSM Air Interface U_m

- Uses Physical **FDMA/TDMA/FDD** physical
  - – In 900 MHz band: 890-915 MHz Uplink band, 935-960 MHz Downlink
  - – Radio carrier is a 200kHz channel => 125 pairs of radio channels
    - Called Absolute Radio Frequency Channel Number (ARFCN)
    - ARFCN numbers given by f(n) = 890 +.2n MHz for Uplink band n = 0, …124
    - Corresponding downlink is f(n) + 45 MHz
    - Channels and ARFCN slightly different in other frequency bands
  - – A TDMA frame is defined on the radio carrier (8 users per carrier)
    - Channel rate is 270.833 kbps
  - – Traffic Channels (voice or data) = 22.8kbps = 1 slot in a TDMA frame

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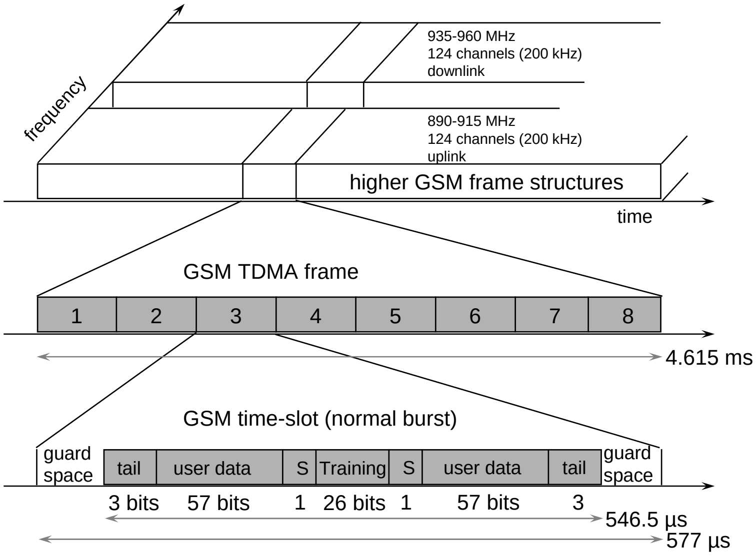
GSM - TDMA/FDMA



frequency

935-960 MHz
124 channels (200 kHz)
downlink

890-915 MHz
124 channels (200 kHz)
uplink

higher GSM frame structures

time

GSM TDMA frame

1 2 3 4 5 6 7 8

4.615 ms

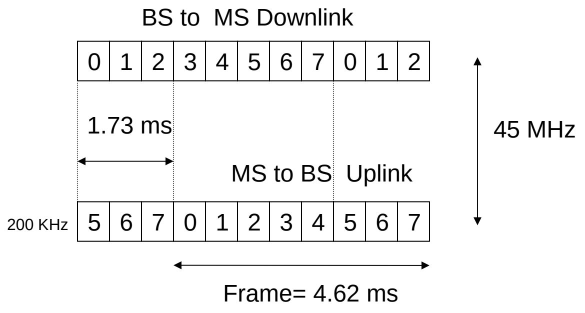
GSM time-slot (normal burst)

guard space	tail	user data	S	Training	S	user data	tail	guard space
	3 bits	57 bits	1	26 bits	1	57 bits	3	

546.5 µs

577 µs

GSM: FDD Channels



Uplink and Downlink channels have a 3 slot offset – so that MS doesn't have to transmit and receive simultaneously
MS can also take measurements during this offset time and delay between next frame

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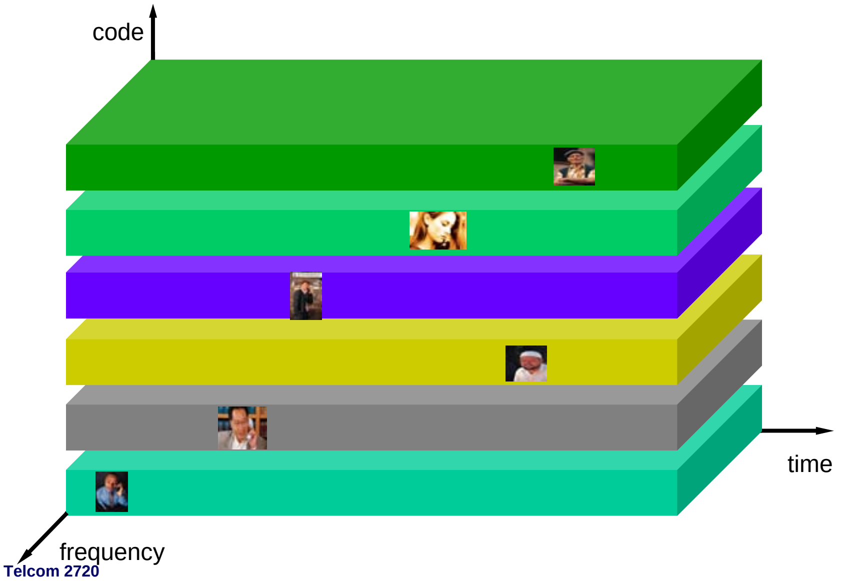
CDMA

- Code Division Multiple Access
  - Narrowband message signal is multiplied by very large bandwidth spreading signal using direct sequence spread spectrum
  - All users can use *same carrier frequency* and may transmit simultaneously
  - Each user has own unique access spreading codeword which is approximately orthogonal to other users codewords
  - Receiver performs time correlation operation to detect only specific codeword, other users codewords appear as noise due to decorrelation
  - Cocktail party example

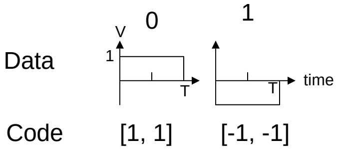
Code Division Multiple Access



Simple example illustrating CDMA

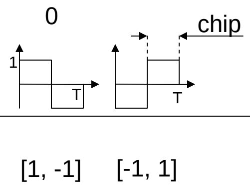
Traditional

- To send a 0, send +1 V for T seconds
- To send a 1, send -1 V for T seconds
- Use separate time slots or frequency bands to separate signals

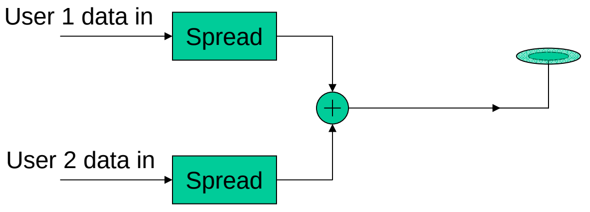


Simple CDMA

- To send a 0, Bob sends +1 V for T seconds; Alice sends +1 V for T/2 seconds and -1 V for T/2 seconds
- To send a 1, Bob sends -1 V for T seconds; Alice sends -1 V for T/2 seconds and +1 V for T/2

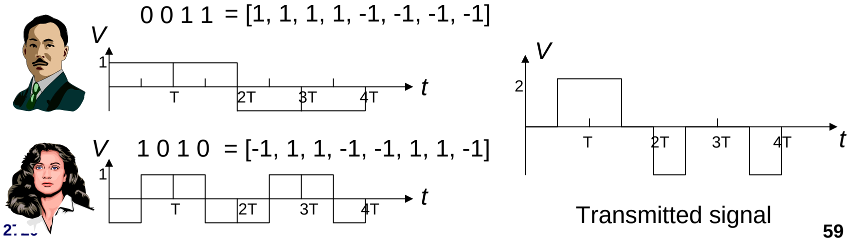


Simple CDMA Transmitter



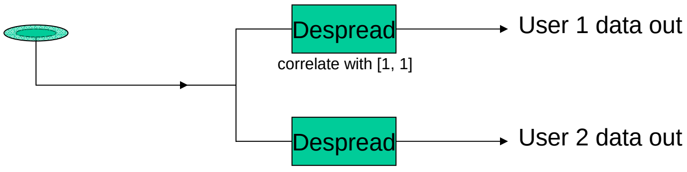
0 0 1 1 = [1, 1, 1, 1, -1, -1, -1, -1]

1 0 1 0 = [-1, 1, 1, -1, -1, 1, 1, -1]



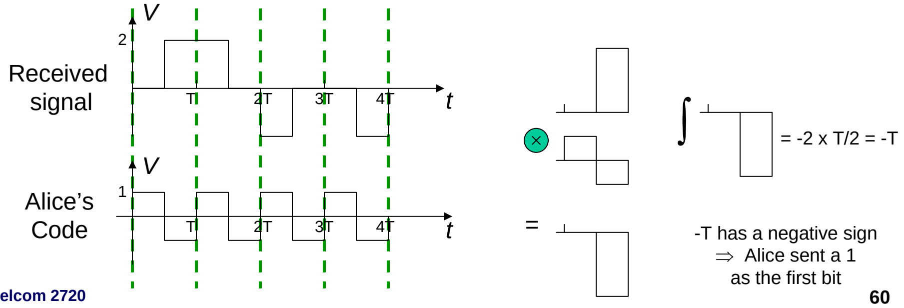
Transmitted signal

Simple CDMA Receiver



correlate with [1, 1]

correlate with [1, -1]



= -2 x T/2 = -T

-T has a negative sign
⇒ Alice sent a 1
as the first bit

Simple CDMA continued

- Proceeding in this fashion for each “bit”, the information transmitted by Alice can be recovered
- To recover the information transmitted by Bob, the received signal is correlated bit-by-bit with Bob’s code [1,1]
- Such codes are “orthogonal”
  - Multiply the codes element-wise
    - [1,1] x [1,-1] = [1,-1]
  - Add the elements of the resulting product
    - 1 + (-1) = 0 => the codes are orthogonal
- In IS-95 standard each orthogonal code is called a Walsh Code and has 64 chips in it

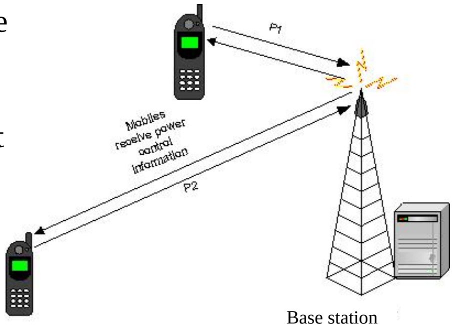
CDMA (cont)

- Advantages
  - No timing coordination unlike TDMA
  - CDMA uses spread spectrum, resistant to interference (multipath fading)
  - No hard limit on number of users
  - Large Capacity Increase
- Disadvantages
  - Implementation complexity of spread spectrum
  - Power control is essential for practical operation
- Used in IS-95, 3G standards (UMTS, cdma 2000)

CDMA Properties: Near-Far Problem

- A CDMA receiver cannot successfully despread the desired signal in a high multiple-access-interference environment

- Unless a transmitter close to the receiver transmits at power lower than a transmitter farther away, the far transmitter cannot be heard
- *Power control* must be used to mitigate the near-far problem
- Mobile transmit so that power levels are equal at base station



Summary

- Diversity Techniques