CDMA Tutorial

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Overview

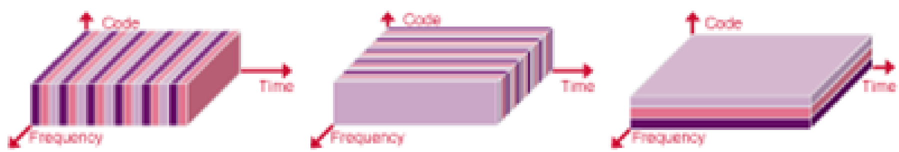
- Common Components
  - Encoding, modulation, spreading
- Common Features/Functionality
  - Power control, diversity, soft handoff
- System Particulars
  - cdmaOne (IS-95)
  - cdma2000

Sources:
1. V. Vanghi, A. Damnjanovic, and B. Vojcic, *The cdma2000 System for Mobile Communications* (Prentice Hall PTR, 2004).
2. V. K. Garg, *IS-95 CDMA and cdma2000* (Prentice Hall PTR, 2000).

CDMA Concept

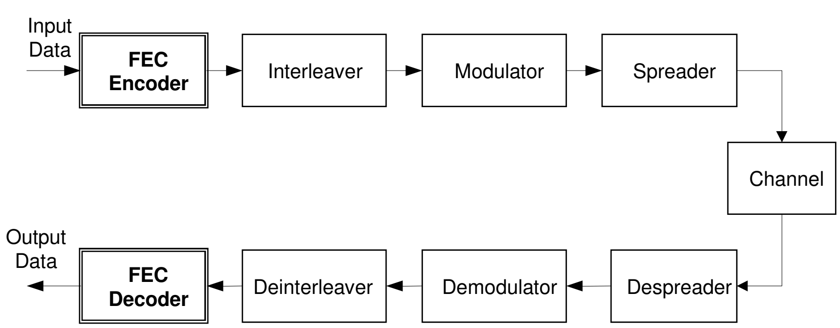
- A way for multiple users to share the channel

Time Division Multiple Access | **Frequency Division Multiple Access** | **Code Division Multiple Access**



3

Generic CDMA Communication System



4

Forward Error Correction (FEC)

- Standard component of most digital communications systems
- Especially important in fading and interference channels
- FEC encoder adds coded redundancy to the information data stream
- Decoder uses the redundancy to correct errors caused by channel impairments (FEC a.k.a. "channel coding")
- Benefits
  - Ability to operate at a lower bit error rate (BER), for a given signal-to-noise-and-interference ratio (SNIR)
  - Ability to operate at a lower SNIR for a given BER ("coding gain")
  - Ability to tolerate more users in a multiuser system

5

Forward Error Correction

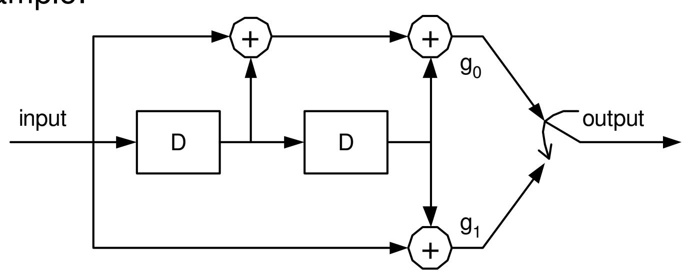
- Costs
  - Added complexity of encoder/decoder
  - Increased bandwidth and/or reduced data rate (exception: trellis-coded modulation)
- Types of codes
  - Block (e.g., Golay, Reed-Solomon)
  - Convolutional
  - Turbo (*i.e.*, concatenated with iterative decoding)

used in current cellular CDMA standards

6

Convolutional Coding

- Implemented using linear shift registers and mod-2 adders
- Example:

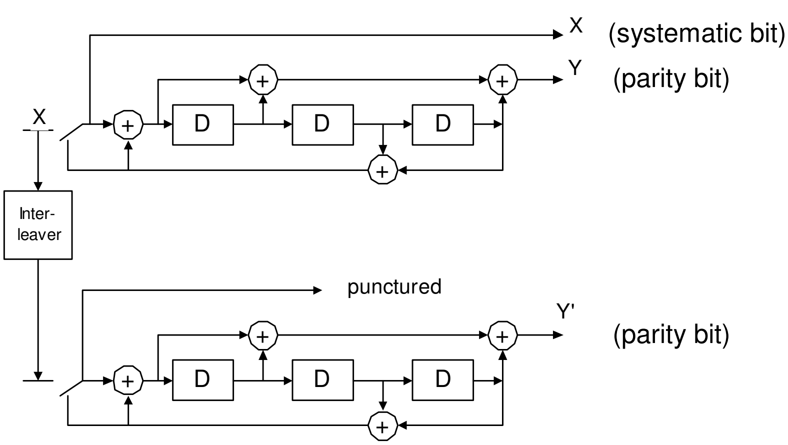


rate: r=1/2 (doubles the sequence length)
constraint length: K=3
generator polynomials: $g_0 = (7)_{oct}$, $g_1 = (5)_{oct}$

7

"Turbo" Coding

- Example: r=1/3 parallel concatenated convolutional code

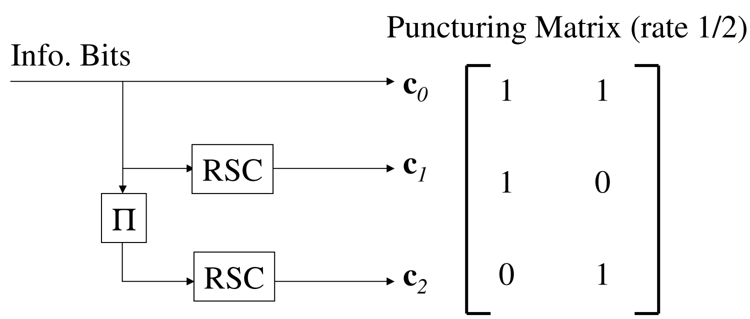


Feed-forward and feedback generator polynomials: $g_1=(15)_{oct}$, $g_0=(13)_{oct}$

8

Puncturing

- For achieving higher code rates (reducing redundancy)
- Example: Puncturing of rate 1/3 turbo code

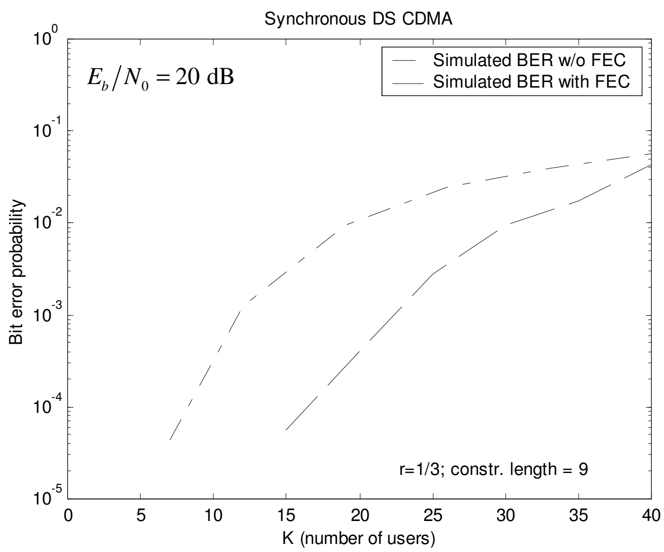


Punctured output sequence:

$$c_{0,1}, c_{1,1}, c_{0,2}, c_{2,2}, c_{0,3}, c_{1,3}, c_{0,4}, c_{2,4}, \ldots$$

9

DS CDMA Performance with FEC



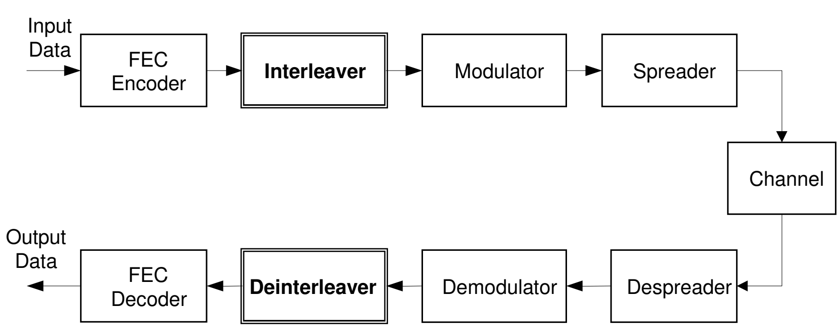
10

Convolutional vs. Turbo Codes

- Turbo Codes
  - Higher coding gain (resilience to noise/interference)
  - Longer latency (better suited for data, not voice)
  - Greater complexity (decoder)

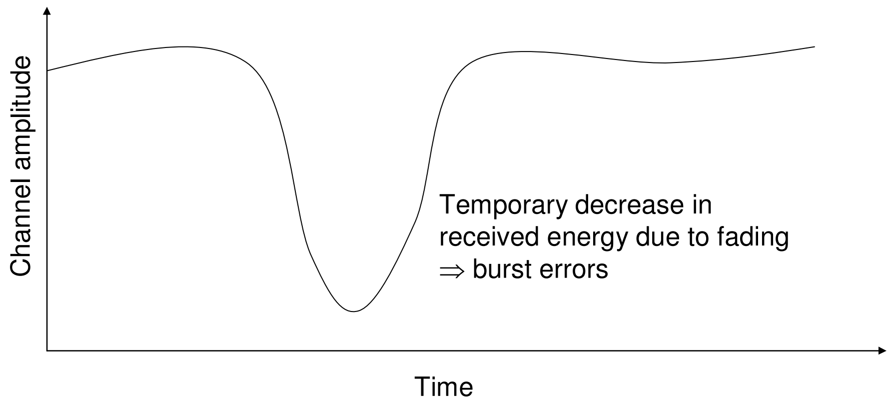
11

Coded Spread Spectrum System



12

Channel Interleaving and Deinterleaving

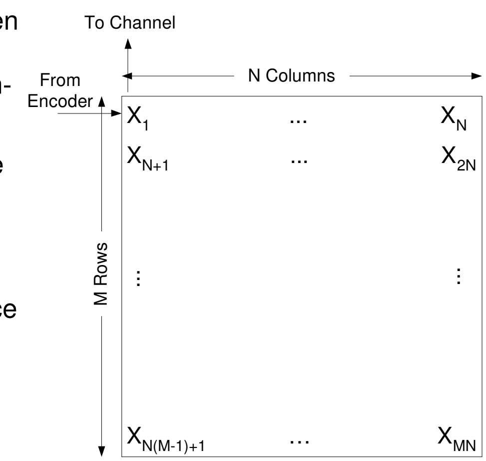


- Can be alleviated by *interleaving* coded symbols at the transmitter and *deinterleaving* them at the receiver

13

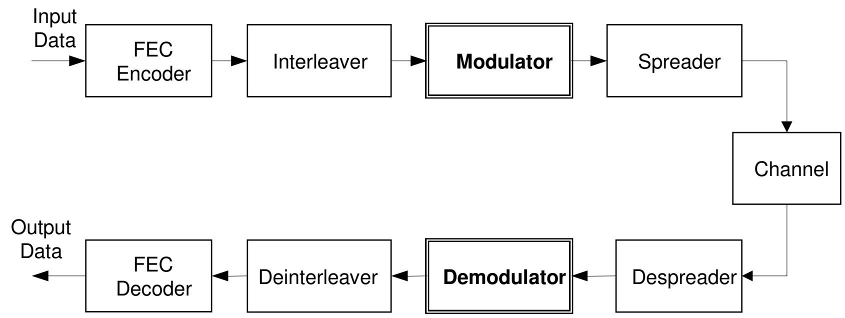
Block Interleaver

- Coded symbols (bits) are written to the interleaver row-wise and read out to the channel column-wise
- Deinterleaver performs reverse operation at receiver
- Adjacent symbols through the channel are separated by *N* positions in the coded sequence
- Cost:
  - Additional memory
  - Introduces delay



14

Coded Spread Spectrum System



15

Modulation

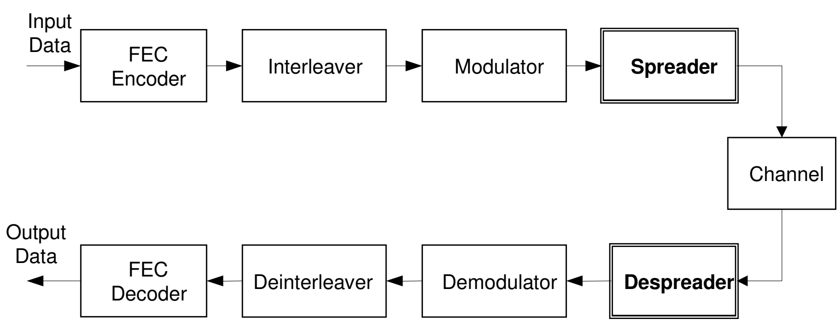
- Coherent Schemes
  - Binary Phase Shift Keying (BPSK)
  - Quaternary Phase Shift Keying (QPSK)
  - 8-PSK
  - 16-QAM

Increasing spectral efficiency. Higher SINR required to achieve a given BER.

- Non-coherent Schemes
  - Orthogonal signals (e.g., Walsh functions)
  - Differential PSK

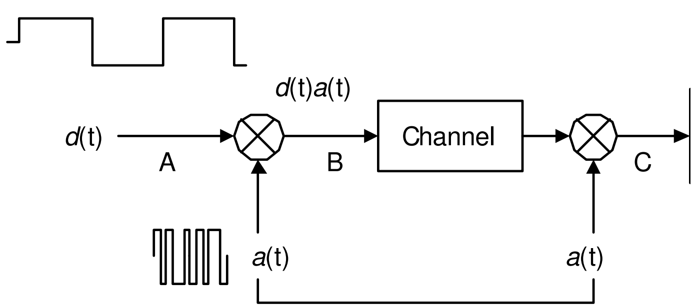
16

Coded Spread Spectrum System



17

Spreading/Despreading



- Each signal (user) is spread with a different spreading sequence (distributes signal power over wider bandwidth).
- Different spreading sequences have low cross-correlation.
- Despreading recovers desired signal while leaving other signals at lower power.

18

Types of Spreading Sequences

- Maximal Length Shift Register (MLSR) sequences
  - Used for generating pseudo-noise (PN) sequences with random-like properties
  - Long periods
- Gold sequences, …
  - Good cross-correlation properties
- Orthogonal sequences
  - Zero cross-correlation (when synchronous)
  - Example: Walsh-Hadamard

19

Walsh-Hadamard Sequences

- Generation

$$\mathbf{H}_1 = [0],\ \mathbf{H}_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix},\ \mathbf{H}_{2N} = \begin{bmatrix} \mathbf{H}_N & \mathbf{H}_N \\ \mathbf{H}_N & \overline{\mathbf{H}}_N \end{bmatrix}$$

- Example

$$\mathbf{H}_4 = \begin{bmatrix} \mathbf{H}_2 & \mathbf{H}_2 \\ \mathbf{H}_2 & \overline{\mathbf{H}}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

- Walsh sequences are rows of Hadamard matrix

20

Overview

- Common Components
- Common Features/Functionality
  - Power Control
  - Diversity
  - Soft Handoff
- System Particulars
  - cdmaOne (IS-95)
  - cdma2000

21

Power Control

- CDMA performance is sensitive to relative received powers of the signals.
- If one signal is too strong, it generates too much interference to the others (near-far effect).
- Goals of Power Control
  - Maintain equal performance for all users
  - Minimize transmitted power to achieve desired QoS
- Types of Power Control
  - Open Loop
  - Closed Loop

22

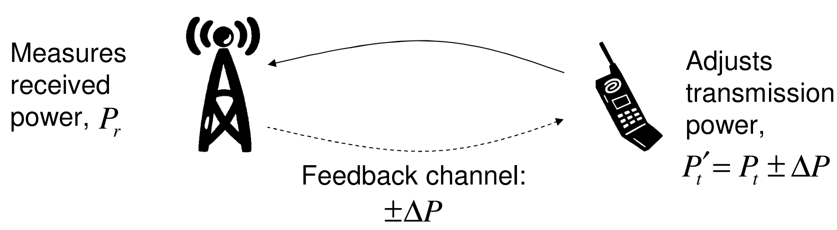
Open Loop Power Control

- Mobile measures received power
- Mobile adjusts transmission power inversely with received power
- Advantage:
  - Does not require communication overhead
- Disadvantage:
  - Ineffective when channels are asymmetric (e.g., frequency division duplex)

23

Closed Loop Power Control

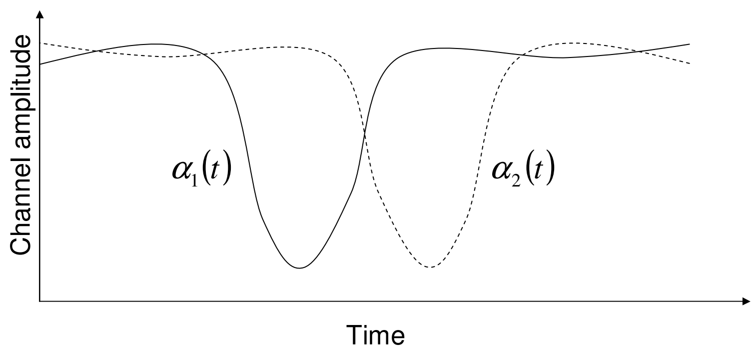
- Base station measures received power from mobile
- Instructs mobile to increase/decrease transmission power via feedback channel



24

Diversity

- Diversity provides multiple, (nearly) independent channels between the transmitter and receiver.
- When one channel is in a deep fade, the other(s) may not be



25

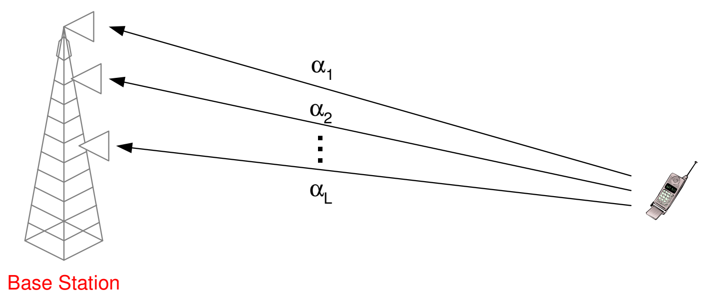
Diversity

- Types of diversity:
  - Frequency
  - Time
  - Antenna (both receive and transmit)
- Receiver combines multiple copies of signal, usually with some knowledge of channel state
- While frequency and time diversity require additional bandwidth or time, antenna diversity does not. Instead, antenna diversity requires additional hardware (antennas and receivers).

26

Receive Antenna Diversity

- Multiple antennas at the receiver
- Energy gain: L-order diversity $\Rightarrow$ up to L-fold increase in SNIR
- Reduced outage probability
- For cellular, usually at the base station



27

Transmit Antenna Diversity

- Multiple antennas at the transmitter
- Techniques for transmit antenna diversity
  - Space-time coding (STC)
  - Orthogonal transmit diversity
- Unlike receive antenna diversity, there is no energy gain, only fading diversity gain.

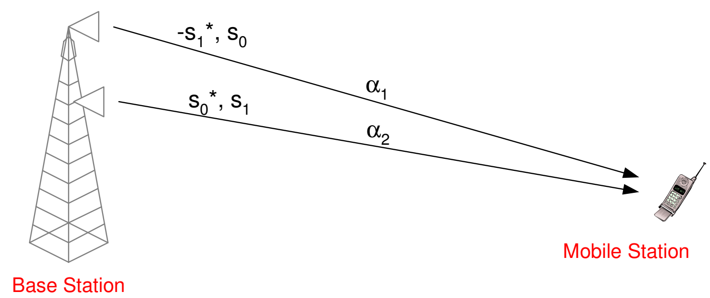
- Space-time coding
  - Combines FEC coding and antenna diversity
  - Can be generalized to include coding and spreading

28

Space-Time Coding Example

- Alamouti encoding and transmission sequence

time	Antenna 0	Antenna 1
$0 \le t < T$	s_0	s_1
$T \le t < 2T$	$-s_1^*$	s_0^*



29

STC Example

- Sampled received signals in the two time slots:

$$r_0 = \alpha_1 s_0 + \alpha_2 s_1 + n_0,$$
$$r_1 = -\alpha_1 s_1^* + \alpha_2 s_0 + n_1.$$

- Combiner:

$$\tilde{s}_0 = \alpha_1^* r_0 + \alpha_2 r_1^*, \qquad \tilde{s}_1 = \alpha_2^* r_0 - \alpha_1 r_1^*, \quad \Rightarrow \quad \tilde{s}_0 = \left(|\alpha_1|^2 + |\alpha_2|^2\right) s_0 + n_0', \qquad \tilde{s}_1 = \left(|\alpha_1|^2 + |\alpha_2|^2\right) s_1 + n_1'$$

- Resulting SNR:

$$SNR_i = \frac{\left(|\alpha_1|^2 + |\alpha_2|^2\right)|s_i|^2}{N_0}$$

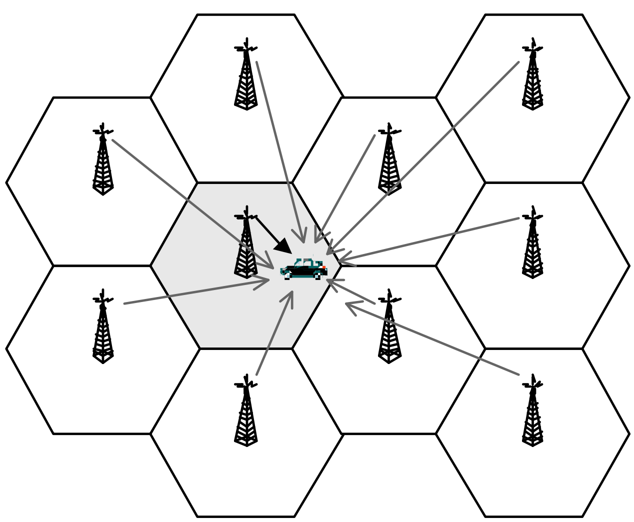
30

Interference in Cellular CDMA

- Universal frequency reuse
  - Reduction of co-channel interference due to processing gain allows frequency reuse factor of 1 (one)
  - (With FDMA and TDMA, co-channel cells must be at a sufficient distance from desired cell)
- Interference sources on
  - Forward link
  - Reverse link

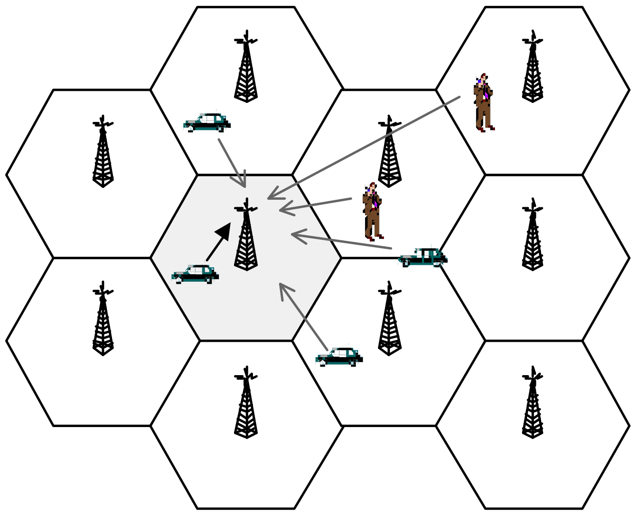
31

Forward CDMA Link Interference



32

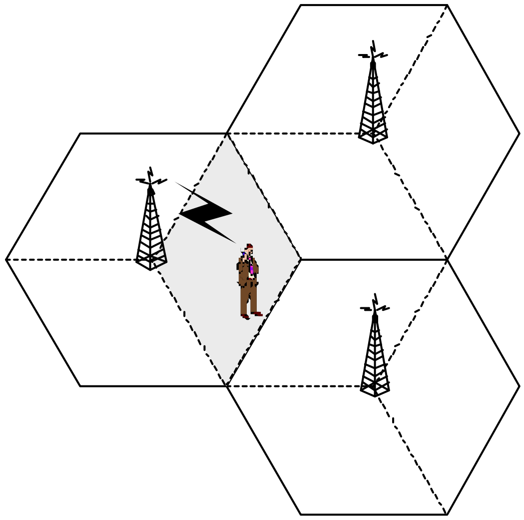
Reverse CDMA Link Interference



33

Cell Sectorization

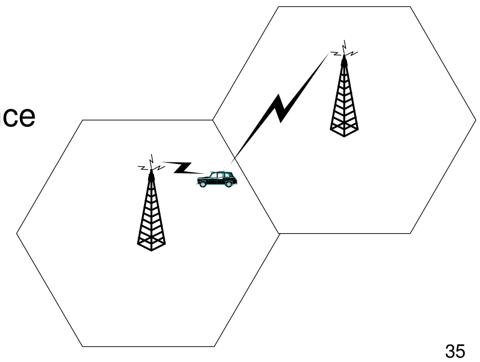
- Example:
  - 3 sectors/cell, 120º antenna beamwidth
  - Reduces interference by a factor of 3
  - Increases capacity by same factor
- 90º and 60º patterns also possible



34

Soft Handoff

- Allows mobile to communicate with new BS w/o interrupting comm. with current BS
- Made possible by universal frequency reuse of CDMA
- A form of macro-diversity
- Cost: increased interference on forward link



35

Overview

- Common Components
  - Encoding, modulation, spreading
- Common Features/Functionality
  - Power control, diversity, soft handoff
- System Particulars
  - cdmaOne (IS-95)
  - cdma2000

36

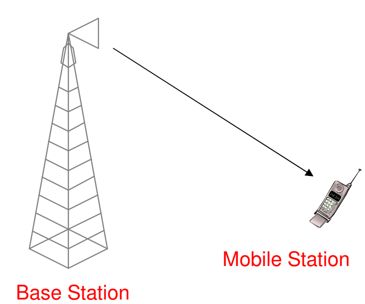
IS-95

- 2G cellular telephony standard designed to be compatible with AMPS frequency band
- Qualcomm produced CDMA/AMPS dual mode phones in 1994
- Each IS-95 channel occupies 1.25 MHz on each one-way link (forward link and reverse link)

37

IS-95 Forward Link Overview

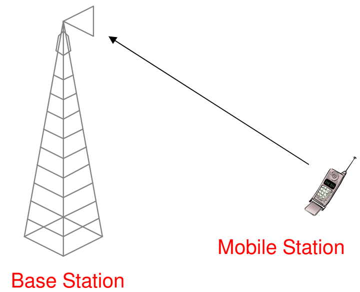
- 64 orthogonal channels
- Pilot signal at higher power level
- Spreading sequences
  - 64 Walsh functions (for channelization)
  - Scrambling code: length 2^{15} PN sequence
    - Reduces interference from co-channel mobiles in different cells/sectors
    - Provides desired wide spectral characteristics
- Power control of FL channels based on measured FER reported by the mobile station (MS) to base station (BS)



38

IS-95 Reverse Link Overview

- Asynchronous signals from mobiles
- Walsh functions used for 64-ary orthogonal signaling
- Offset QPSK (OQPSK) modulation
- Spreading sequences
  - Long code: length $2^{42}-1$ PN sequence (unique for each user)
  - Short code: length 2^{15} PN sequence
- Tight power control of each user's transmitter power
  - Based on received SIR measured by BS
  - Faster than forward link power control



39

Forward Link Channels

- Control channels
  - One Pilot channel
  - One Synch channel
  - One to seven Paging channels
- Traffic channels
  - For voice/data
  - Ranging from 55 to 61 channels
- Each channel assigned one of 64 Walsh functions
- See Fig. 6-1 of [Garg]

40

Pilot Channel

- Provides phase reference to the mobile for coherent detection
- Also used for comparisons of signal strength between different base stations (handoff decision)
- Carries no data/signaling information
- Signal level is 4-6 dB higher than that of traffic channel
- Pilot PN sequence
  - Short code, period 2^{15} = 32,768 chips (@1.2288 Mcps $\Rightarrow$ 75 pilot code repetitions every 2 sec)
  - All base stations use the same sequence but with different offsets (64 chip offsets $\Rightarrow$ 512 unique offsets)
- See Fig. 7-7 of [Garg]

41

Synch Channel

- Used with pilot channel to acquire initial time synchronization
- Only the synch channel message is transmitted over this channel
  - System time
  - Offset local time
  - Pilot short PN sequence offset
  - Long-code state
  - Daylight saving time indicator
  - Etc.
- See Fig. 7-9 of [Garg]

42

Paging Channel

- Used to transmit control info to the MS
  - When a mobile receives a call, it receives a page from the BS on an assigned paging channel
  - Acknowledgments to access requests made by the mobile station
  - Supplementary service info (e.g., caller ID, no. of messages waiting)

43

Forward Traffic Channels

- Rate sets
  - RS1: 1200, 2400, 4800, 9600 bps
  - RS2 (optional): 1800, 3600, 7200, 14400 bps
- Each forward traffic channel consists of
  - 1 Fundamental code channel
  - 0-7 Supplemental code channels
  - Mobile power control subchannel
    - ± 1 dB power control commands every 1.25 ms
- Decimated long code used for privacy
- See Fig. 7-21 of [Garg]

44

Forward Traffic Channel Parameters

Parameters	Data Rate (bps)				Units
	9600	4800	2400	1200	
PN chip rate	1.2288	1.2288	1.2288	1.2288	Mcps
Code rate	1/2	1/2	1/2	1/2	bits per code symbol
Code symbol repetition	1	2	4	8	repeated symbols per code symbol
Modulation symbols rate	19,200	19,200	19,200	19,200	sps
PN chips per modulation symbol	64	64	64	64	PN chips per modulation symbol
PN chips per bit	128	256	512	1024	PN chips per bit

45

Reverse Link Channels

- Access channel
  - For control control information (e.g., call origination, response to paging)
- Traffic channel
- See Fig. 6-2 of [Garg]

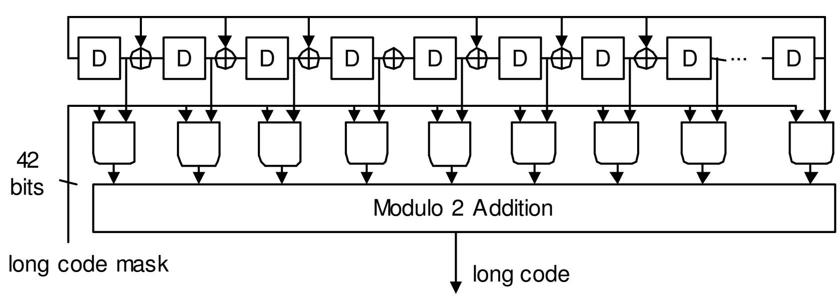
46

Access Channel

- Up to 32 access channels (more than one MS can share an access channel)
- Each access channel has a unique access channel long code, access number and paging channel number associated with it
- Messages carried
  - Registration message (for mobility mgmt, paging)
  - Origination message
  - Page response message
  - Etc.
- See Fig. 7-16 of [Garg]

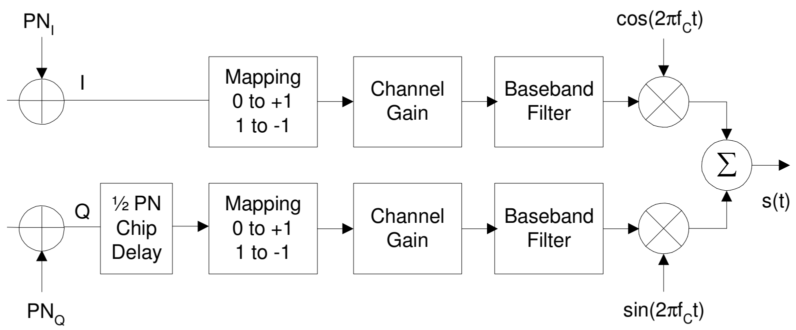
47

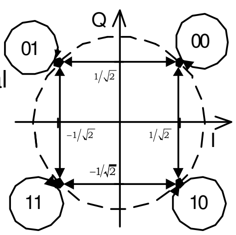
Long PN Sequence Masking



48

Offset QPSK Modulation





OQPSK signal constellation

- Results in non-zero crossing envelope
- Allows for a simpler power amplifier at MS

49

Reverse Traffic Channels

- 62 reverse traffic channels, differentiated by user-specific long codes
- Processing similar to that of access channel, except for
  - More data rates
  - Inclusion of “data burst randomizer”
    - Masks out redundant symbols of lower data rate streams
    - Reduces reverse link interference by reducing transmitted power during quiet periods of speech
- See Figs. 7-26, -27, -28 of [Garg]
- See Table 6-6 of [Garg]

50

Reverse Traffic Channel Parameters

Parameter	9600 bps	4800 bps	2400 bps	1200 bps	Units
PN chip rate	1.2288	1.2288	1.2288	1.2288	Mcps
Code rate	1/3	1/3	1/3	1/3	bits per code symbol
Code symbol repetition	1	2	4	8	repeated symbols per code symbol
Code symbol rate	3×9600 =28,800	28,800	28,800	28,800	sps
Modulation	6	6	6	6	code symbol per modulation symbol
Modulation symbol rate	28,800/6 =4800	4800	4800	4800	sps
Walsh chip rate	64×4800= 307.2	307.2	307.2	307.2	kcps
PN chips per Walsh chip	4	4	4	4	PN chips per Walsh chip

51

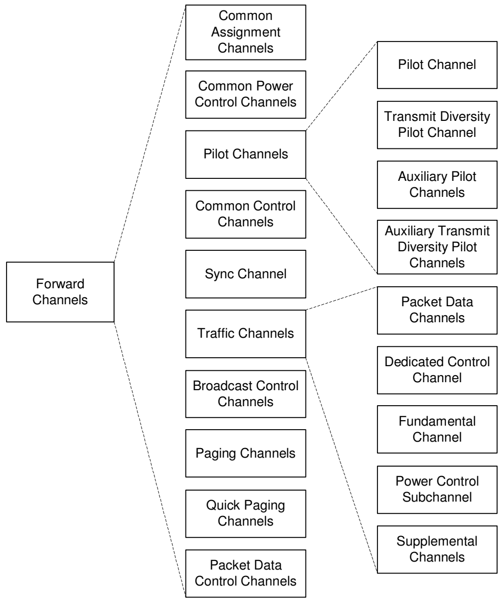
cdma2000

Features

- Support of voice and low to high data rates
- Multiple channel sizes
  - Spreading Rate 1 (SR1): 1.2288 Mcps a.k.a. “single carrier” or “1×”
  - SR3, “multicarrier” or “3×”
    - Forward link: 3 carriers spread @ 1.2288 Mcps
    - Reverse link: 1 carrier spread @ 3.6864 Mcps
- Support for advanced antenna technologies
- Backward compatibility with IS-95 (cdmaOne)

52

cmda2000 Forward Link Channels



53

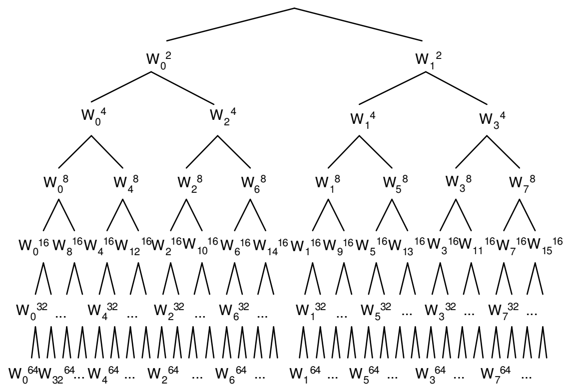
Forward Link Features

- Multiple carriers
- Orthogonal channels using Walsh codes
- QPSK modulation (and 8-PSK, 16-QAM for packet data channel)
- Fast closed-loop power control
- Transmit antenna diversity
- FEC
  - Convolutional codes for voice and data
  - Turbo codes for long data frames

54

Orthogonal Spreading

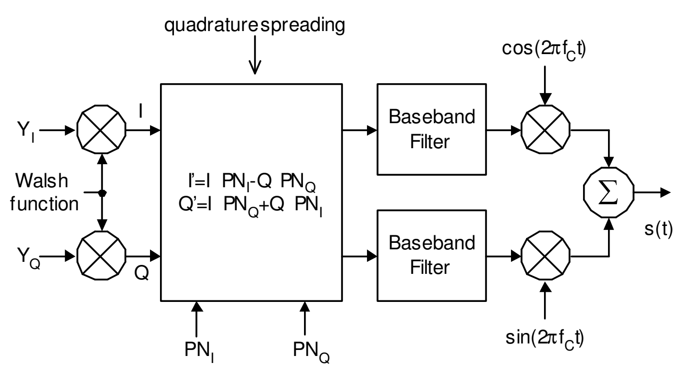
- Using variable length Walsh functions
- Different bit rates use different length Walsh codes, ranging from 4 to 128 chips
- Allocated to maintain orthogonality



55

Quadrature Spreading

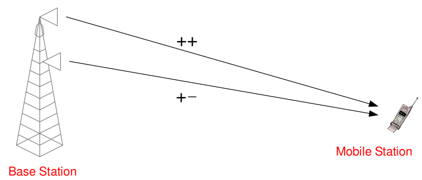
- QPSK modulation
  - Distinct data on in-phase and quadrature channels
  - Allows for stronger coding while maintaining data rate
- Complex spreading using length 2^{15} short PN codes



56

Transmit Diversity Modes

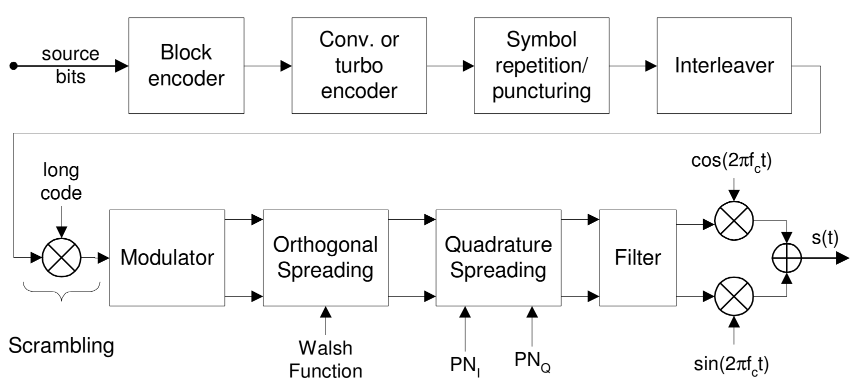
- Orthogonal Transmit Diversity (OTD)
  - Multiplexes consecutive coded bits onto different antennas
  - Coded bits are spread with a length-2 Walsh function for orthogonality between the two antennas



- Space Time Spreading (STS)
  - Uses the Alamouti space-time code discussed in the last lecture

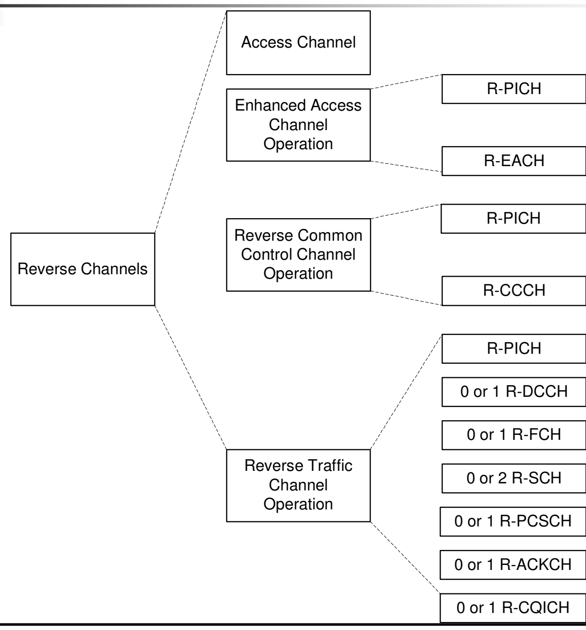
57

Forward Link Block Diagram



58

cmda2000 Reverse Link Channels



59

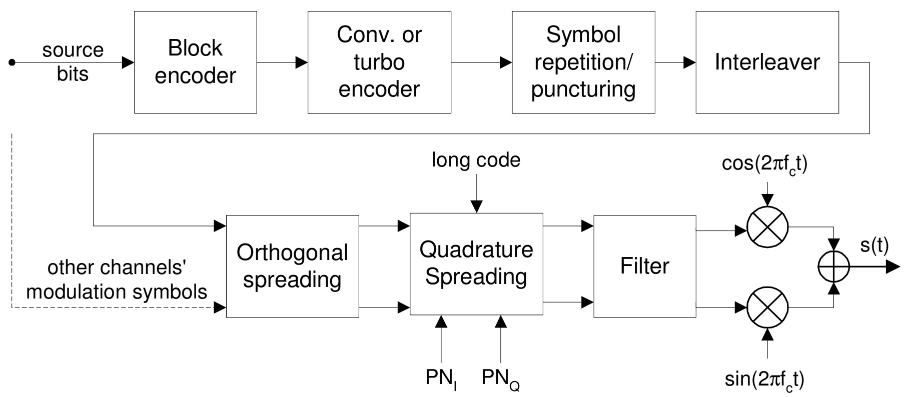
Reverse Link Features

- Code multiplexing using orthogonal Walsh functions
- Pilot signal transmitted by each user
- BPSK modulation with coherent detection
  - Limited power ⇒ larger carrier phase estimation error
  - RL not dimension-limited

  } ⇒ BPSK instead of QPSK
- User-specific long PN code
- Complex spreading with OQPSK

60

Reverse Link Block Diagram



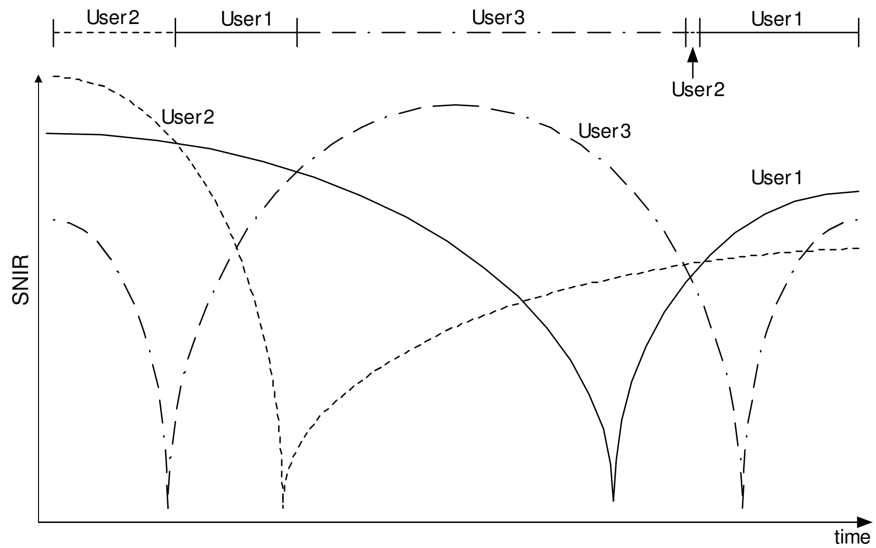
61

High Data Rate Service

- Implemented on forward link packet data channel (FL-PDCH)
- Carries bursty, high speed, non-real-time data
- Shared channel
  - BS transmits to only one mobile at a time
- Data is code-multiplexed using up to 28 length-32 Walsh codes
- Adaptive modulation using QPSK, 8-PSK, 16-QAM
- Adaptive coding: code rates range from 1/5 to 3/4
- Exploits multiuser diversity with opportunistic scheduling

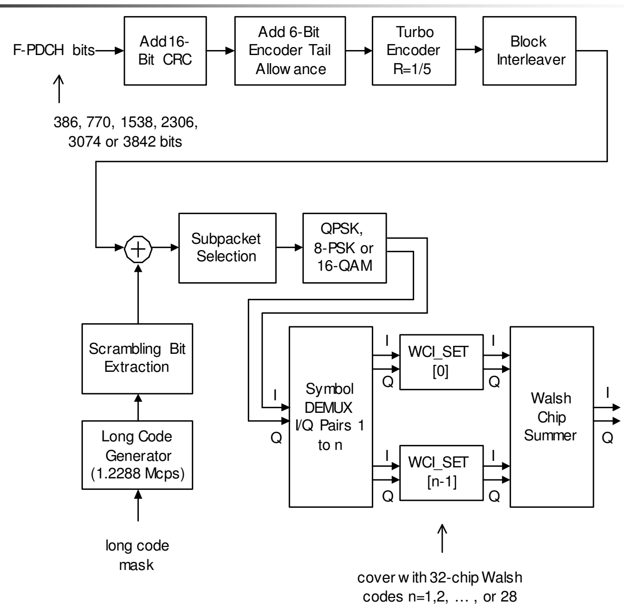
62

Multiuser Diversity and Scheduling



63

Forward Link Packet Data Channel



64