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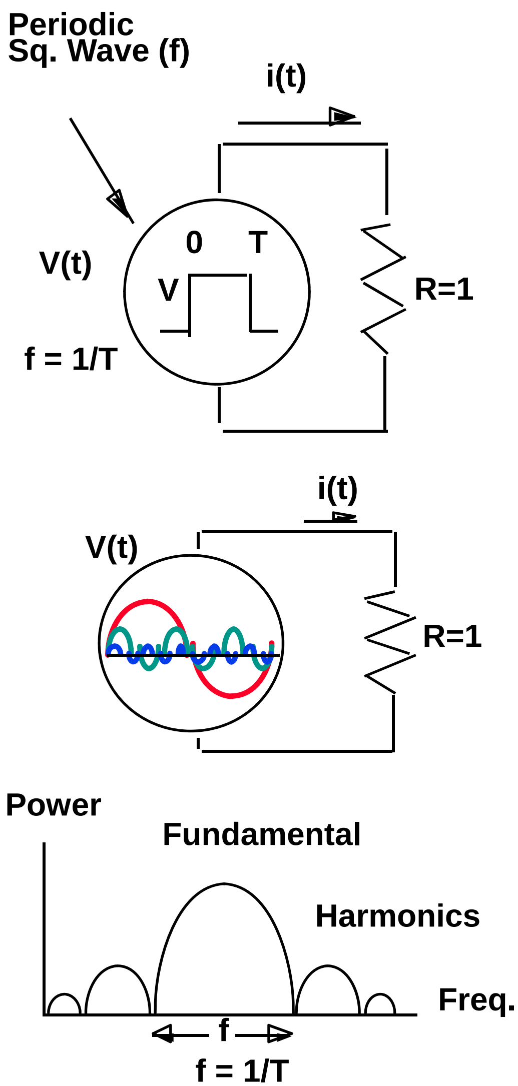
Lecture 23
Code Division Multiple Access (CDMA)

TOPICS

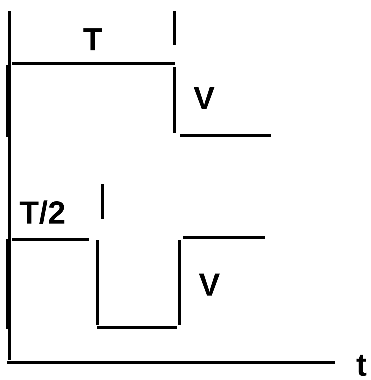
- **Describe Spread Spectrum**
- **Provide DS-CDMA concept**
- **Recognize Orthogonal codes**
- **Illustrate how it is implemented in IS-95 standard**
- **Examine forward and reverse link waveform**
- **Describe soft hand-off & power control issues**

Spectrum

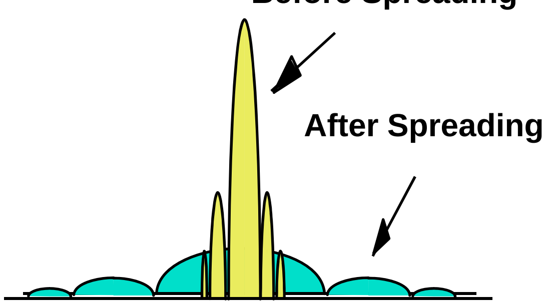


- A discrete time signal is composed of an infinite number of harmonically related sinusoidal waves
  - *- Spectrum*
- The associated power is due to infinite number of sinusoidal components:
  - main lobe corresponds to the fundamental frequency
  - side lobes correspond to harmonic components
- The bandwidth of the power spectrum is proportional to the frequency

Spectrum Spreading



Time

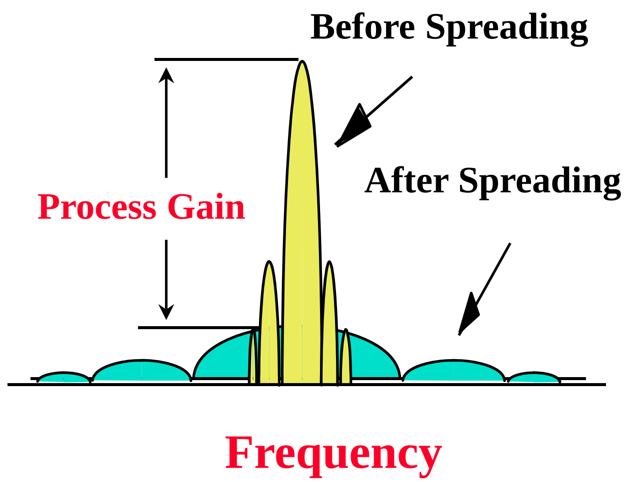


Frequency

- Spectrum spreading is accomplished by increasing the frequency of the discrete time signal
- A high frequency signal has wider spectrum than a low frequency signal
- A low frequency signal has higher power amplitude than a low high power signal
- This is due to conservation of energy

- This is one of the key element in DS-CDMA
- It also leads to the concept of “Process Gain”

Process Gain



- **Process gain is due to spectrum spreading**
- **Defined as**

$$G = 10\log\left(\frac{BW}{R_b}\right)$$

BW=Bandwidth after spreading

R_b= Original bit rate (Before spreading)

CDMA Process Gain: *Illustration*

- **Spreading gain gives CDMA a big advantage over traditional, non-spread-spectrum systems**
- **Example: CDMA vs TDMA Cellular**
  - **TDMA Cellular**

    BW = 30 KHz   Rb = 10 KHz

    Process Gain = 10 Log (30/10) = 4.7 db
  - **CDMA**

    BW = 1.23 MHz Rb = 10 KHz

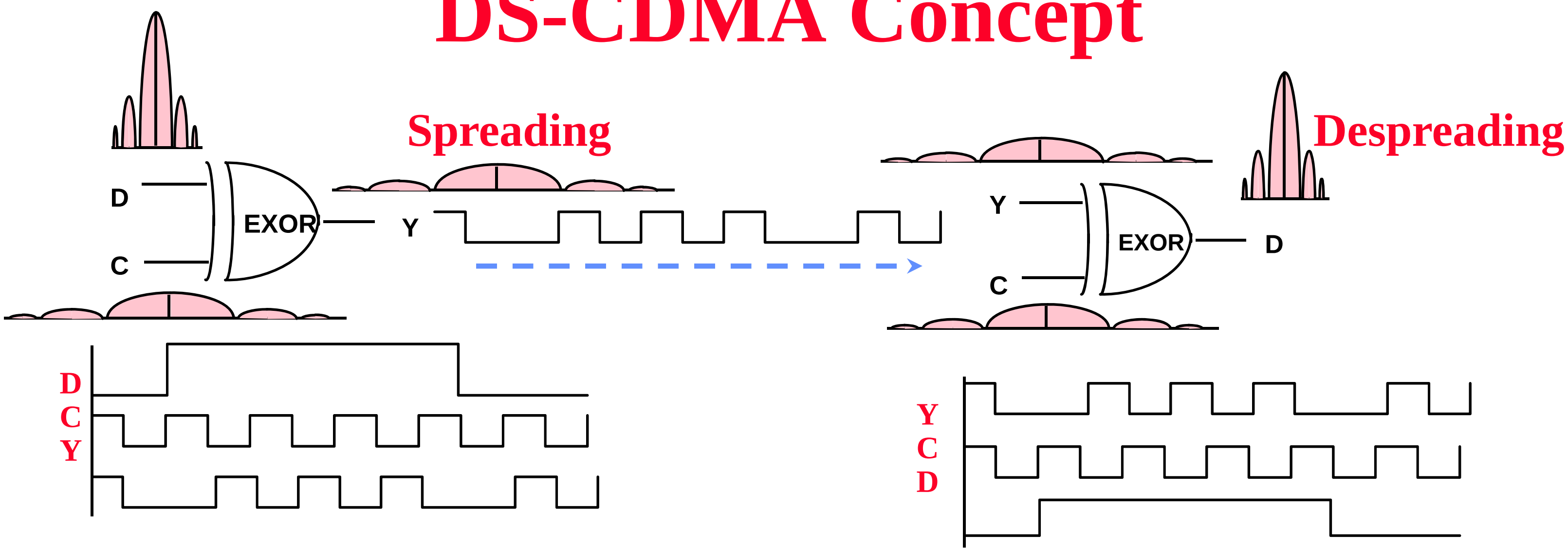
    Process Gain = 10 Log (1230/10) = 20.9 db
  - **CDMA advantage: 20.9 - 4.7 = 16.2 dB**

    this advantage assumes only one user on CDMA system

    doubling number of users reduces advantage 3 db
  - **with 16 users, CDMA still has 4 db advantage over TDMA**

- **How can we spread the bandwidth of information ?**

DS-CDMA Concept



Spreading:

- D = low speed data
- C = high speed PN Code
- Y = D EXOR C

Despreading:

- Y = high speed received data
- C = same PN Code
- D = Y EXOR C
  = D EXOR C EXOR C

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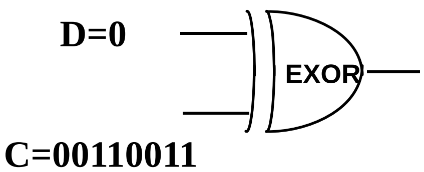
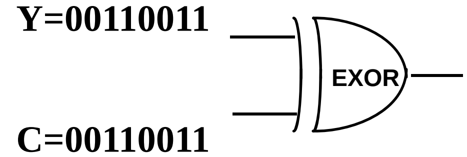
DS-CDMA: *Example-1*

Transmitter



$$\begin{array}{r} D = \quad 0 \\ \oplus \\ \underline{C = 00110011} \\ Y = 00110011 \end{array}$$

Receiver



$$\begin{array}{r} Y = 00110011 \\ \oplus \\ \underline{C = 00110011} \\ D = 00000000 \end{array}$$

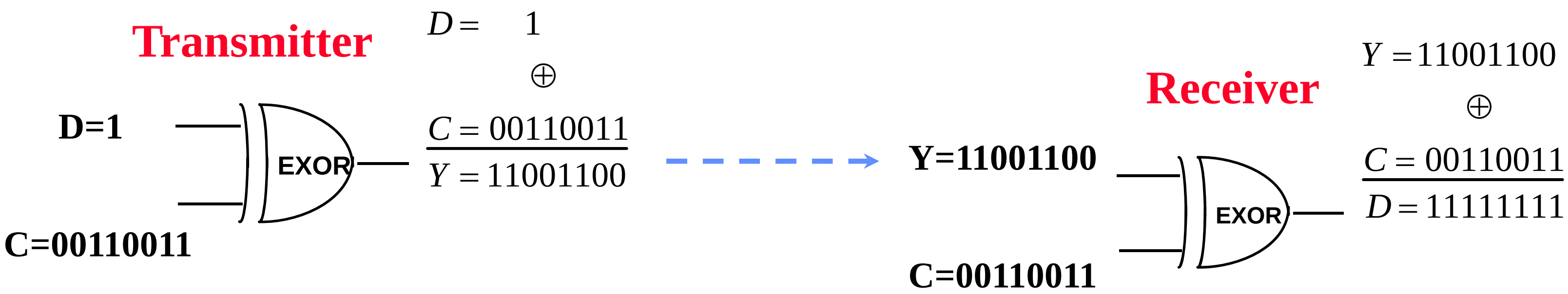
Spreading:

- D = 0
- C = 00110011 (8-bit code)
- Y = D EXOR C
  = 0 EXOR 00110011
  = 00110011

Despreading:

- Y = 00110011
- C = 00110011 (same code)
- D = Y EXOR C
  = 00110011 EXOR 00110011
  = 00000000

DS-CDMA: *Example-2*



Spreading:

- D = 1
- C = 00110011 (8-bit code)
- Y = D EXOR C
  = 1 EXOR 00110011
  = 11001100

Despreading:

- Y = 11001100
- C = 00110011 (same code)
- D = Y EXOR C
  = 11001100 EXOR 00110011
  = 11111111

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Our Observations

Spreading Process:

- A PN code multiplied by BIN-0 (binary zero) produces the same PN code:

  Bin-0 EXOR PN code = PN code

  0 EXOR 00110011 = 00110011

- A PN code, multiplied by BIN-1 produces the inverse code, also known an "Antipodal code"

  BIN-1 EXOR PN code = PN code

  1 EXOR 00110011= 11001100

Despreading Process:

- A PN code multiplied by the same PN code, produces "Zeros"

  PN code EXOR PN code = 0

  00110011 EXOR 00110011 = 0

- A PN code multiplied by the antipodal code, produces "Ones"

  PN code EXOR Antipodal code = 1

  00110011 EXOR 11001100 = 1

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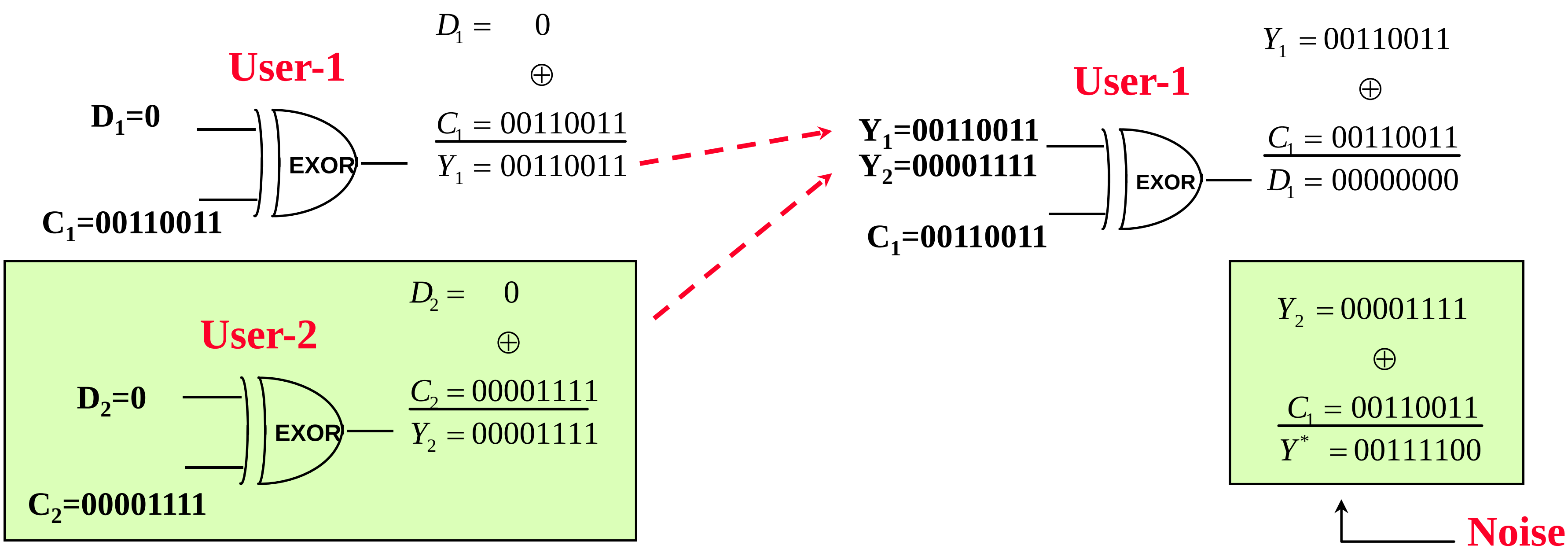
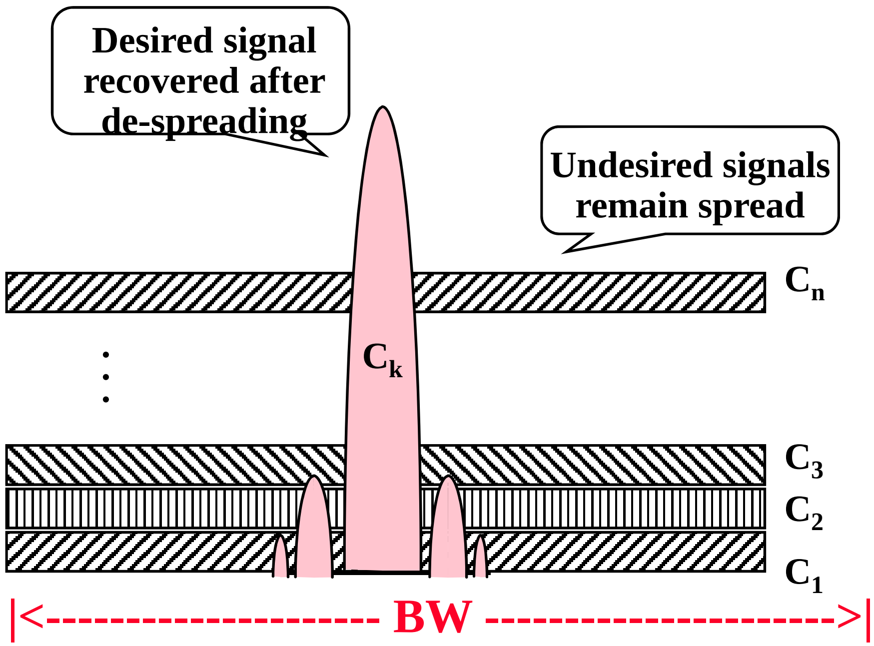
Multi User DS-CDMA



- **Data from User-1:**
  - **Tx Data D1=0, Code C1=00110011, Output Y1=D1 EXOR C1= 00110011**
  - **Rx Data D1=Y1 EXOR C1= 00110011 EXOR 00110011 = 0 (O.K)**
- **Data from User-2:**
  - **Tx Data D2=0, Code C2=00001111, Output Y2=D2 EXOR C2 = 00001111**
  - **Rx Data D2 =Y2 EXOR C1= 00001111 EXOR 00110011 = 00111100 (spread, noise)**
- **All users, other than the desired signal, appears as noise**

How Many users can Share the Same Spectrum ?



- Each user contributes noise to the system
- Therefore the number of users that can share the same bandwidth would be given by the Process gain minus Total noise contributions
- Also, an additional ... eded ... performance

- This is CDMA capacity issue
- We shall explore this later when it is appropriate

PN Codes and Orthogonal Codes

Example:
n = 64 (IS-95 CDMA)
Number of PN Sequences
= 2^{64} - 1
= 1.8447 x 10^{19}
Out of 1.8447 x 10^{19} PN sequences, only 64 of them are orthogonal codes

- **An n-bit PN code has 2^n - 1 PN sequences**
- **Out of these PN sequences, only n-codes are orthogonal**
- **A 64-bit PN code has 1.8447 x 10^{19} PN sequences**
- **Only 64 of them are Orthogonal codes**
- **Orthogonal codes have zero cross-correlation properties**

Properties of Orthogonal Codes

Example-1:
x = 0 0 1 1
y = 0 1 1 0

-1 -1 1 1
-1 1 1 -1
R_{xy} = 1 -1 1 -1 = 0

Example-2:
x = 0 0 1 1
y = 1 1 0 0

-1 -1 1 1
1 1 -1 -1
R_{xy} = -1 -1 -1 -1 = - 4

- **A pair of code:**

  $x_1, x_2, \ldots, x_n$

  $y_1, y_2, \ldots, y_n$

  is Orthogonal if the cross-correlation is zero.
- **This is given by:**

$$R_{xy}(0) = \sum_{i=1}^{n} x_i y_i = 0$$

- **An Orthogonal code has equal number of 1's and 0's. But not all codes having equal number of 1's and 0's are orthogonal**

Properties of Orthogonal Codes: *Cont.*

Example-1:
x = 0 0 1 1
y = 0 1 1 0

$$\begin{array}{r} -1\ -1\ 1\ 1 \\ \underline{-1\ \ 1\ 1\ -1} \\ R_{xy} = 1\ -1\ 1\ -1 = 0 \end{array}$$

Example-2:
x = 0 0 1 1
y = 1 1 0 0

$$\begin{array}{r} -1\ -1\ 1\ 1 \\ \underline{1\ \ 1\ -1\ -1} \\ R_{xy} = -1\ -1\ -1\ -1 = -4 \end{array}$$

Antipodal

- Orthogonal codes are binary numbers (2^n)
- An Orthogonal code has equal number of 1's and 0's
- A pair of code:

  $x_1, x_2, \ldots, x_n$

  $y_1, y_2, \ldots, y_n$

  is Orthogonal if the cross-correlation is zero.
- This is given by:

$$R_{xy}(0) = \sum_{i=1}^{n} x_i y_i = 0$$

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Properties of Orthogonal Codes: *Cont.*

8-bit Orthogonal code has 16 Bi-Orthogonal codes

	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0
1	0	1	0	1	0	1	0	1
2	0	0	1	1	0	0	1	1
3	0	1	1	0	0	1	1	0
4	0	0	0	0	1	1	1	1
5	0	1	0	1	1	0	1	0
6	0	0	1	1	1	1	0	0
7	0	1	1	0	1	0	0	1
8	1	1	1	1	1	1	1	1
9	1	0	1	0	1	0	1	0
10	1	1	0	0	1	1	0	0
11	1	0	0	1	1	0	0	1
12	1	1	1	1	0	0	0	0
13	1	0	1	0	0	1	0	1
14	1	1	0	0	0	0	1	1
15	1	0	0	1	0	1	1	0

- **An n-bit Orthogonal code has:**
  - **n Orthogonal codes and**
  - **n antipodal codes**
- **Total number of codes = 2n**
- **The 2n code-set is known as Bi-Orthogonal code-set**
  - **An 8-bit Orthogonal code has 16 Bi-Orthogonal codes**
  - **A 64-bit Orthogonal code has 128 Bi-Orthogonal code-set**

Generation of Orthogonal Codes

C1	1st Quadrant	2nd Quadrant
C2	3rd Quadrant	4th Quadrant

b	b
b	$\bar{b}$

Orthogonal		
C1	0	0
C2	0	1

Antipodal	
1	1
1	0

Repeat the process for longer codes

- Step-1: Divide N x N matrix as FOUR Quadrants
- Step-2: Make 1st, 2nd and 3rd quadrant identical & Invert the 4th
  - b is the bit value 0 or 1
- Orthogonal Code: C1= 0 0

  C2= 0 1
- Antipodal Code: C1= 1 1

  C2= 1 0

Generation of Long Orthogonal Codes

2 x 2

$$\begin{array}{c|c|c} C1 & 0 & 0 \\ \hline C2 & 0 & 1 \end{array}$$

4 x 4

$$\begin{array}{c|cc|cc} C1 & 0 & 0 & 0 & 0 \\ C2 & 0 & 1 & 0 & 1 \\ \hline C3 & 0 & 0 & 1 & 1 \\ C4 & 0 & 1 & 1 & 0 \end{array}$$

8 x 8

$$\begin{array}{c|cc|cc|cc|cc} C1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ C2 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ C3 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ C4 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ \hline C5 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ C6 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ C7 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ C8 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{array}$$

- Begin with a 2 x 2 matrix as before
- Generate a 4 x 4 by repeating 2 x 2
- Generate a 8 x 8 by repeating 4 x 4

so on . . .

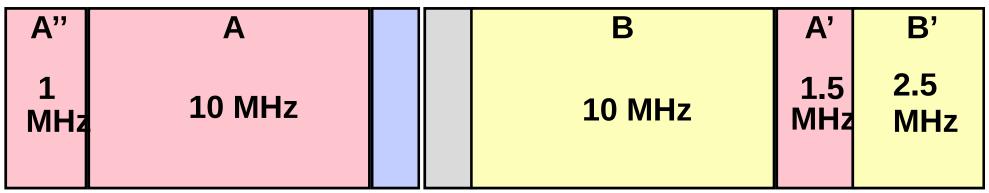
This process was developed by J. L Walsh in 1923
- known as Walsh Code

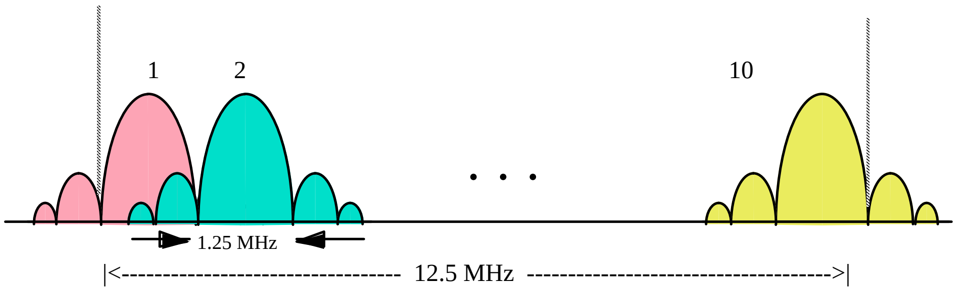
codes

IS-95A Codes & Their Usage

- **Walsh Code:**
  - **64 bits long, 64 Orthogonal codes, Code rate = 1.2288 Mb/s**
  - **Unique identifier for mobiles**
  - **Walsh Code Assignment:**
    - » **W0 = Walsh code 0, used in Pilot Channel**
    - » **W1-W7: Used in paging channels (7-paging channels)**
    - » **W32: Used in Sync. channel**
    - » **W8 to W31 and W33 to W63: Used in Traffic channels**
- **Long PN Code:**
  - **42-bits long, 2^{42}-1=4.398 x10^{12} PN codes, Code rate=1.2288Mb/s**
  - **Used for reverse channel spreading and data scrambling**
- **Short PN-Code:**
  - **15-bits long, 2^{15}-1=32,767 PN codes, Code rate=1.2288 Mb/s**
  - **Used for cell identification in reused cells (Similar to SAT in**

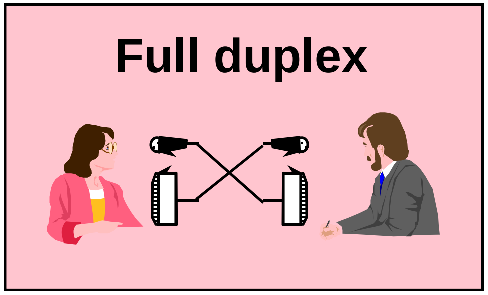
IS-95A DS-CDMA
Spectrum

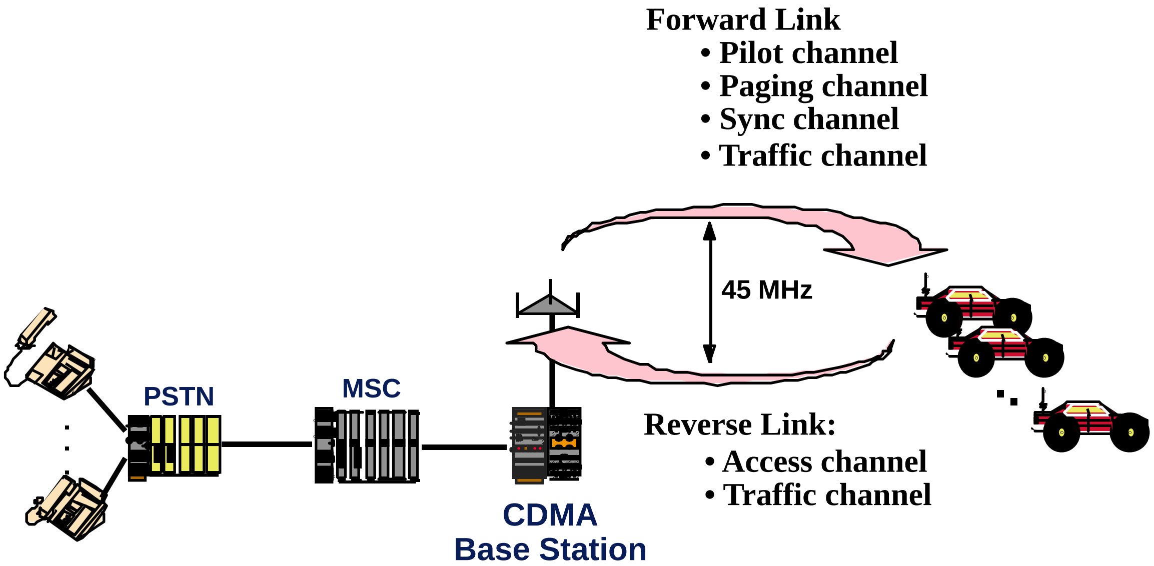




- The existing 12.5 MHz cellular spectrum (A or B) is divided into TEN CDMA bands
- Each band is 1.25 MHz
- Each 1.25 MHz band supports 64 Walsh codes

CDMA Architecture

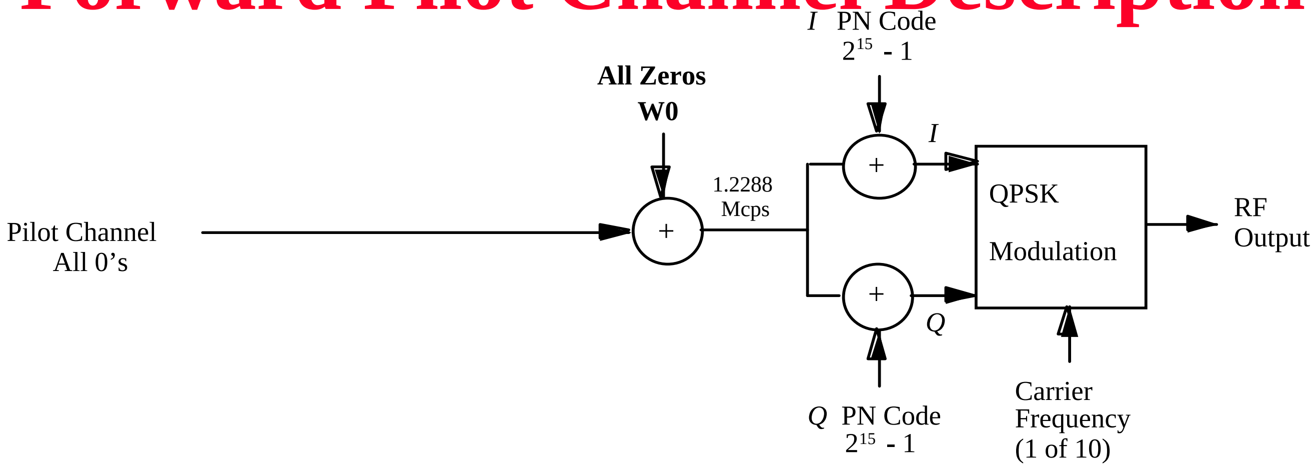




- **Forward link -- *Base to mobile***
  - **Pilot channel**
  - **Paging channel**
  - **Sync. channel**
  - **Traffic channel**

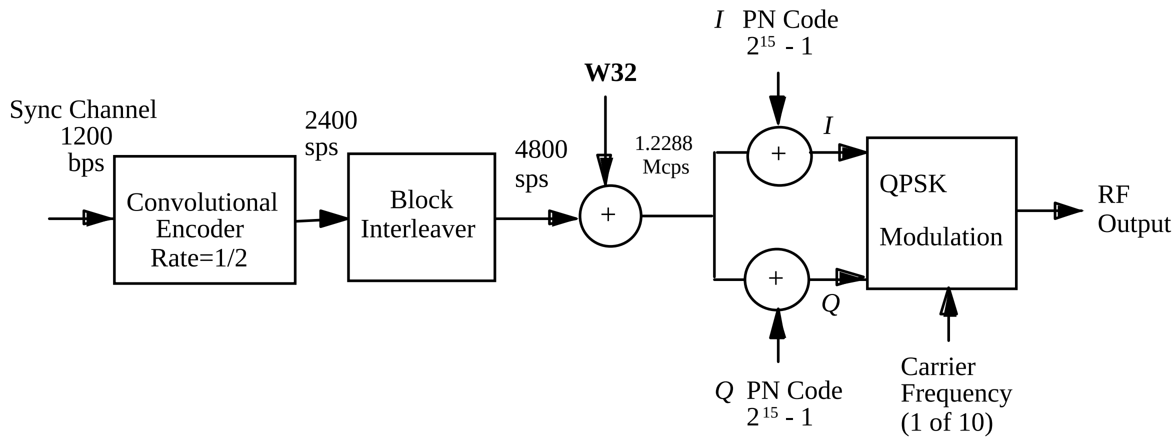
- **Reverse link -- *Mobile to base***
  - **Reverse access channel**
  - **Reverse traffic channel**

Forward Pilot Channel Description



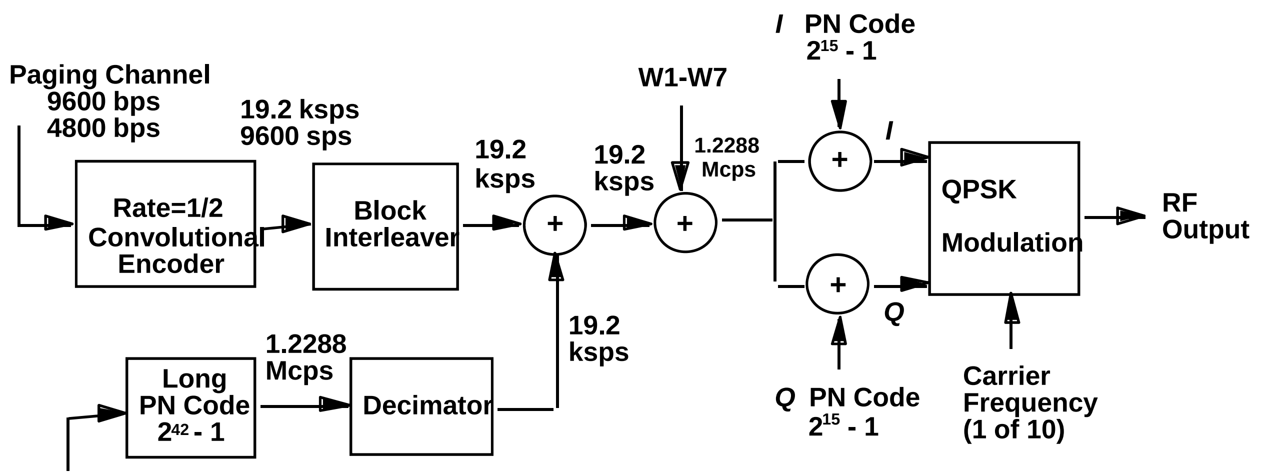
- **All zero, uncoded spread spectrum channel**
- **Spreading Code: W0, 64-zeros**
- **Continuously transmitted from the base station**
- **Each base station uses one of 2^{15}-1 PN sequences to identify a forward pilot channel (there are 512 PN offsets)**
- **Provides phase & Timing reference**
- **Provides signal strength to the mobile**

Forward Sync. Channel Description



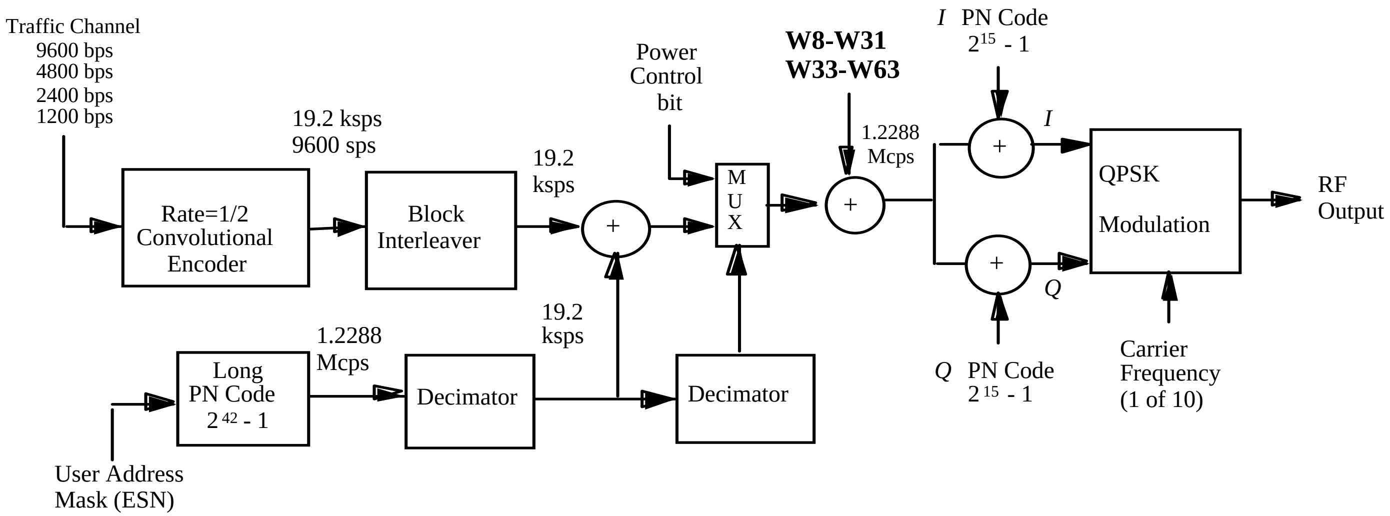
- **Rate 1/2 convolutionally encoded spread spectrum channel**
- **Spread by means of W32 and then MOD2 added (EXOR) with a unique 15-bit PN code (same PN code as the pilot)**
- **Modulated and transmitted**
- **Provides:**
  - **Unique timing for synchronization**
  - **Networks ID's**

Forward Paging Channel Description



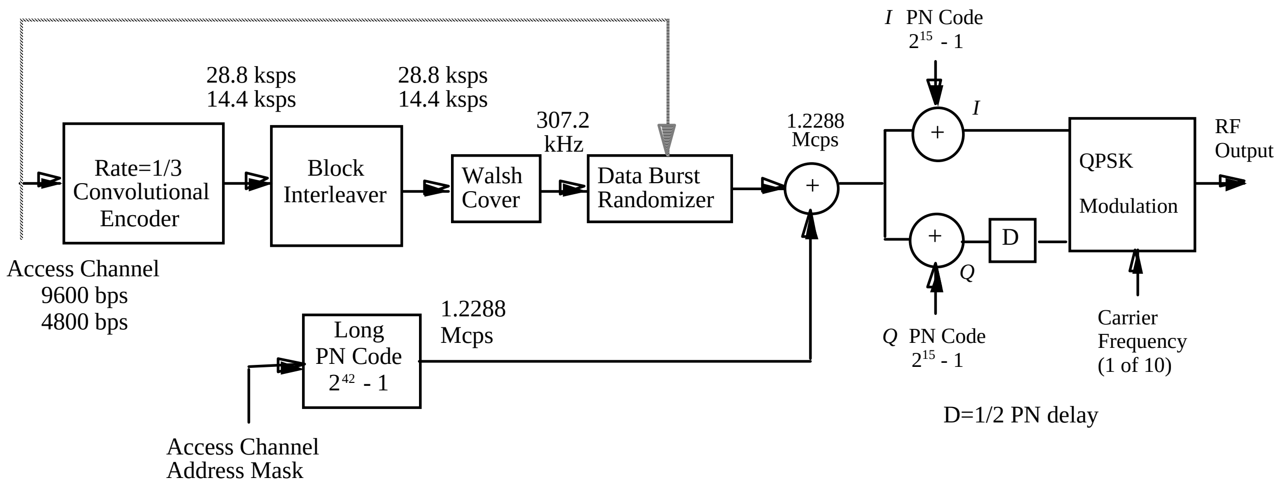
- Spread by means of W1-W7
- Uses the same PN code (offset)
- Pages a mobile
- Provides system parameter MSG
- Assigns traffic channel
- Overhead information
- Neighbor list

Forward Traffic Channel Description



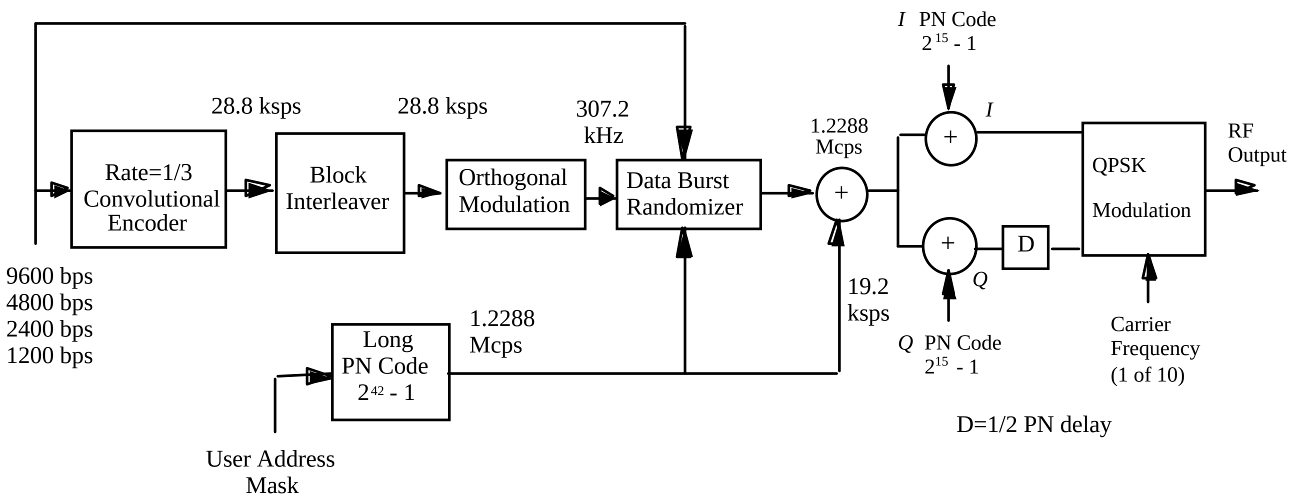
- Spread by means of W8-W31 and W33-W63
- Uses the same PN code (offset)
- Used for voice communications, Signaling
- Provides power control
- Assigns traffic channel
- Overhead information
- Neighbor list

Reverse Access Channel Description



- **Works in association with Forward Paging Channel**
- **Spread by means of Long PN code (42-bits, 1.2288Mb/s)**
- **Used for Call origination, system access**
- **Channel request**
- **Page response**
- **Registration**

Reverse Traffic Channel Description



- Used for voice communications
- Spread by means of Long PN code (42-bits, 1.2288Mb/s)
- Same short PN offset
- Response to command
- Seeks information from the base

CDMA Capacity *WITHOUT* Cellular Features

- Carrier to interference ratio is given by

$$\frac{C}{I} = \frac{R_b \times E_b}{N_o \times W} \qquad \textbf{(A)}$$

where

E_b = energy per bit

R_b = bit rate

N_o = thermal noise

W = transmission bandwidth

- In CDMA, the interference is due to all users except one

$$I = C(N-1)$$

$$\frac{C}{I} = \frac{1}{N-1} \qquad \textbf{(B)}$$

- Equating (A) and (B) we get

$$\frac{1}{N-1} = \frac{R_b \times E_b}{N_o \times W}$$

$$N = 1 + \frac{W / R_b}{E_b / N_o}$$

$\boxed{W/R_b = \text{Process gain}}$

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CDMA Capacity *WITH* Cellular Features

- In the cellular environment, the maximum achievable capacity is given by

$$N = 1 + \frac{W / R_b}{E_b / N_o} \bullet \frac{F}{D} \bullet S \bullet H$$

F=frequency reuse factor (1)

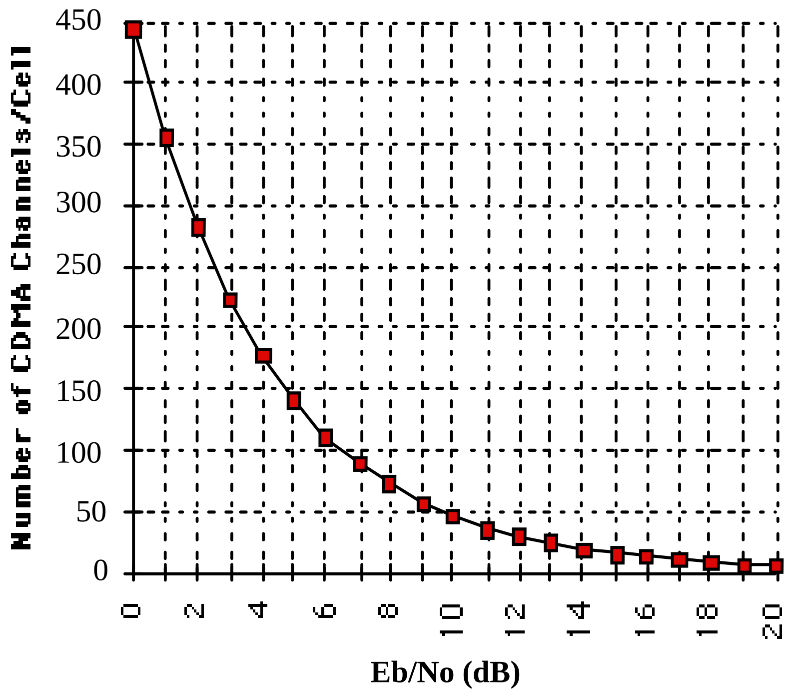
d=voice duty cycle (0.45)

S=sectorization factor (3)

H=soft hand-off factor

W=1.25MHz

R_b=9600bps



Low Eb/No is the key to enhance CDMA capacit

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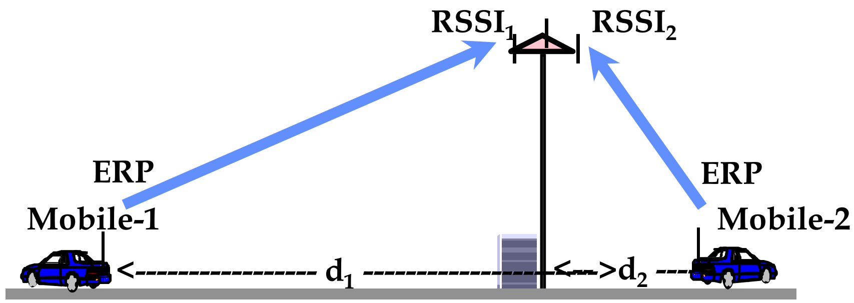
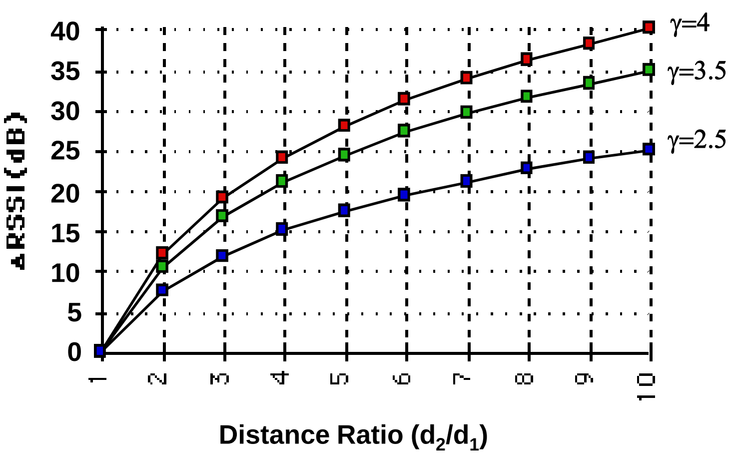
Why CDMA Power Control





γ = Propagation Constant

Near-Far Problem:

- If the mobiles are permitted to transmit the same power from different distances, the ratio of received signal level would be:

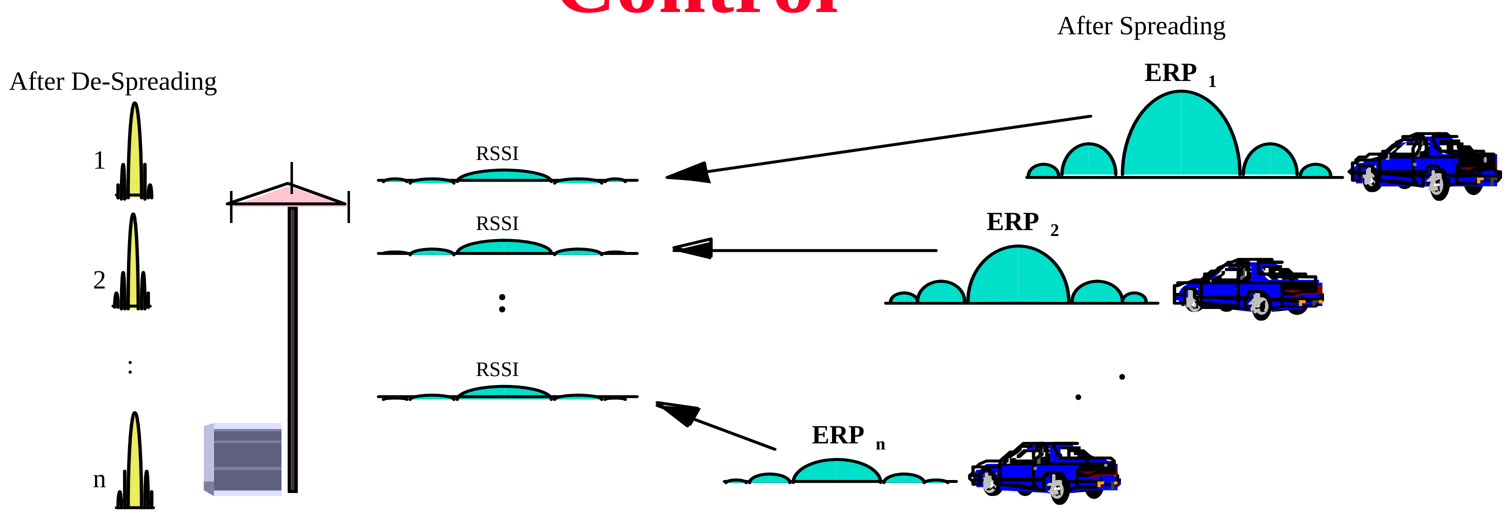
$$\frac{RSSI_1}{RSSI_2} = \left(\frac{d_2}{d_1}\right)^{\gamma}$$

- This implies that if d1=4d2, and prop. constant=4 (Urban), RSSI from d2 will be 256 times stronger and the base station will be unable to recover the other mobile
- Therefore power control is necessary so that RSSI's are same

Power Control Process in CDMA

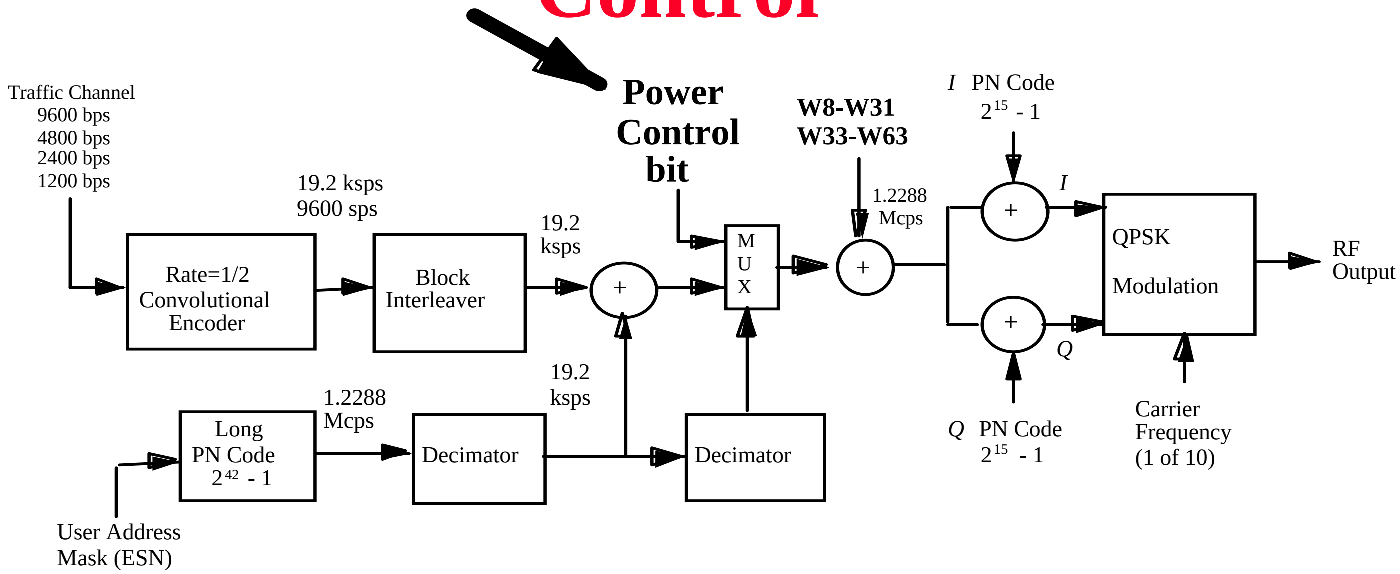
- Three step process:
  - Reverse link open loop power control
  - Reverse link closed loop power control
  - Forward link power control

Reverse Link Open Loop Power Control



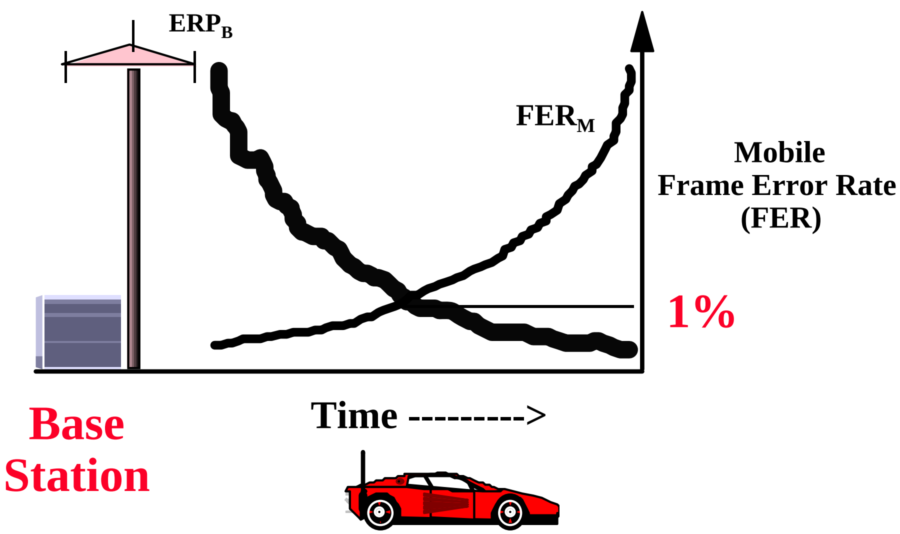
- Each mobile computes differential path loss and adjusts its transmit power so that the received signal level at the base is constant
- The total received power from all mobiles determines the system capacity

Reverse Link Closed Loop Power Control



- **Reverse link closed loop power control is accomplished by a power up/down command from the base station**
- **A single power control bit is inserted in the data stream, rate=1.25ms:**
  - **1 for 0.5dB up, and 0 for 0.5dB down**
  - **Upon receiving, the mobile control its power accordingly**

Forward Link Power Control



- Base station reduces ERP
- Mobile computes FERRO
- if FER=1%, stop reducing ERP

- The base station reduces its power while the mobile computes Frame Error Rate (FER)
- When the mobile detects 1% FER, it sends a request to stop the power reduction
- The process occurs every 15 to 20 ms
- This adjustment process is limited to only 6dB in 0.5dB steps because all

CDMA Hand-Off

- **CDMA to CDMA Soft Hand-Off**
  - **Mobile is directed to adjacent cell or sector, same frequency, different code, without dropping the serving code**
  - **Mobile keeps both channels during the process**
  - **Once the new link is well established, the original link is dropped**
  - **This process is known as “Soft-Hand Off” or “Make before Break”**
- **CDMA to CDMA Hard Hand-Off**
  - **Mobile is directed to a different CDMA frequency**
  - **Voice is muted momentarily during this process**
- **CDMA to AMPS Hard Hand-Off**
  - **A dual mode mobile is directed to an AMPS channel**
  - **Voice is muted momentarily during this process**

End of Lecture 23