Evolution of wireless networks - 2G to 3G, 4G, and beyond

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Session 1

Objectives

Technology Overview

- At the end of this section, the following objectives will have been accomplished:
- Point out basic concepts of various technologies
- Introduce principles of direct spread-spectrum communication
- Recognize the Forward and Reverse CDMA channels and review the codes which define them
  - Briefly discuss the role of each CDMA channel in call processing
  - Understand the origins of interference on the CDMA reverse link
  - Briefly discuss the four methods of CDMA Power Control and how they work
- Explore basic CDMA system RF planning rules
  - Review principles of Pilot PN offset planning
  - Understand guard bands and basic CDMA frequency planning

What is a Channel?

***Channel**: An individually-assigned, dedicated pathway through a transmission medium for one user's information*

The physical transmission medium is a resource that can be subdivided into individual channels according to different criteria depending on the technology used:

Here's how the three most popular technologies establish channels:

- **FDMA *Frequency* Division Multiple Access**
  - each **user** on a different frequency
  - a channel is a ***frequency***
- **TDMA *Time* Division Multiple Access**
  - each **user** on a different window period in time ("time slot")
  - a channel is a specific ***time slot*** on a specific ***frequency***
- **CDMA *Code* Division Multiple Access**
  - each **user** uses the same frequency all the time, but mixed with different distinguishing code patterns
  - a channel is a unique ***code pattern***

FDMA



TDMA



CDMA



What is CDMA



Code

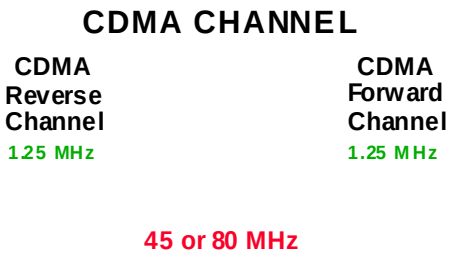
Division

Multiple

Access

Defining Our Terms

- CDMA Channel or CDMA Carrier or CDMA Frequency
  - Duplex channel made of two 1.25 MHz-wide bands of electromagnetic spectrum, one for Base Station to Mobile Station communication (called FORWARD LINK or the DOWNLINK) and another for Mobile Station to Base Station communication (called the REVERSE LINK or the UPNLINK)
  - in 800 Cellular these two simplex 1.25 MHz bands are 45 MHz apart
  - in 1900 MHz PCS they are 80 MHz apart
- CDMA Forward Channel
  - the 1.25 MHz Forward Link
- CDMA Reverse Channel
  - the 1.25 MHz Reverse Link



- CDMA Code Channel
  - each individual stream of 0's and 1's contained in either the CDMA Forward Channel or in the CDMA Reverse Channel
  - Code Channels are characterized (made unique) by mathematical codes
  - code channels in the forward link: Pilot, Sync, Paging and Forward Traff channels
  - code channels in the reverse link: Access and Reverse Traffic channels

What is Multiple Access?

Multiple Access: *Simultaneous private use of a transmission medium by multiple, independent users.*

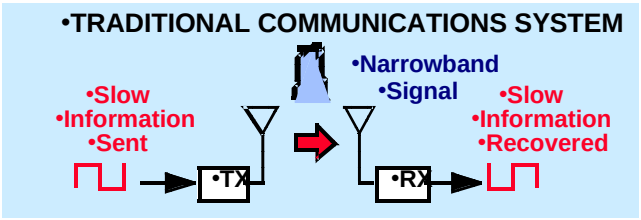
Since the beginning of telephony and radio, system operators have tried to squeeze the maximum amount of traffic over each circuit

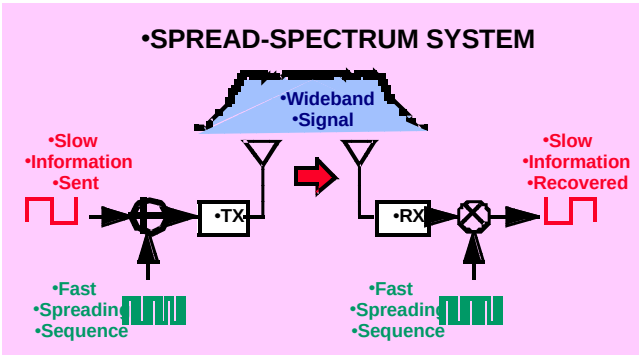
- Types of Media -- Examples:
  - Twisted pair - copper
  - Coaxial cable
  - Fiber optic cable
  - Air interface (radio signals)
- Advantages of Multiple Access
  - Increased capacity: serve more users
  - Reduced capital requirements since fewer media can carry the traffic
  - Decreased per-user expense
  - Easier to manage and administer



Each pair of users enjoys a dedicated, private circuit through the transmission medium, unaware that the other users exist.

Spread Spectrum Principles



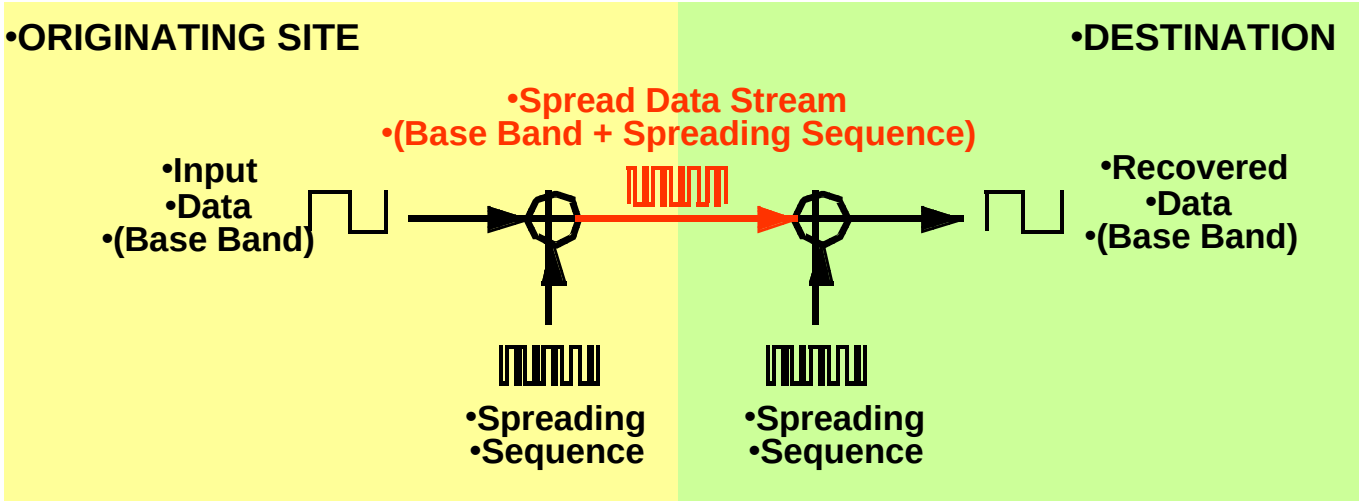


Spread Spectrum Payoff : Processing Gain

- Traditional radio communication systems transmit data using the minimum bandwidth required to carry it as a narrowband signal
- Direct-Sequence Spread spectrum systems mix their input data with a fast spreading sequence and transmit a wideband signal
  - The spreading sequence is independently regenerated at the receiver and mixed with the incoming wideband signal to recover the original data
- The de-spreading gives substantial ***gain*** proportional to the bandwidth of the spread-spectrum signal
- The gain can be used to increase system performance and range, or allow multiple coded users, or both

Why do we call this a “Spread Spectrum” technique?

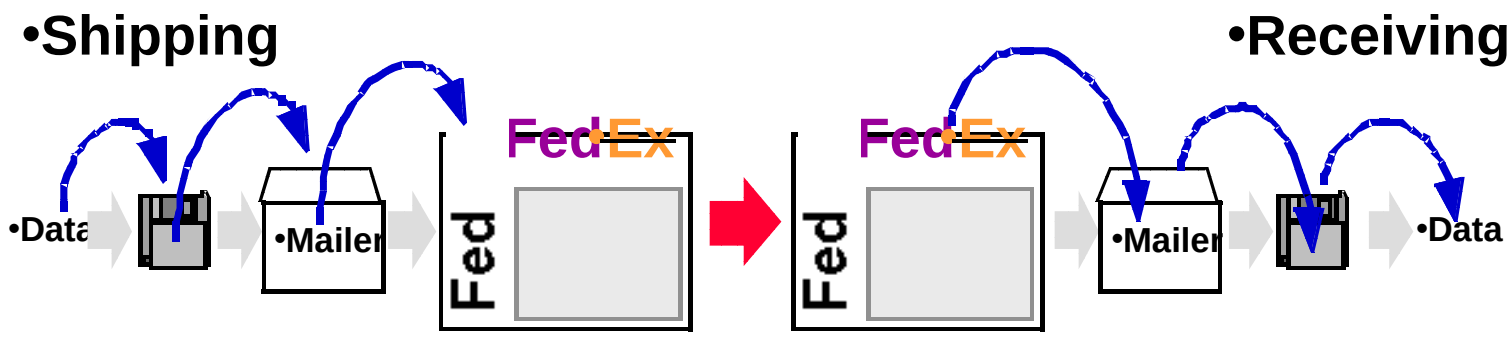
CDMA Spreading Principle: Anything We Can Do, We Can Undo



- Any data bit stream can be combined with a spreading sequence
- The resulting signal can be de-spread and the data stream recovered if the original spreading sequence is available and properly timed
- After de-spreading, the original data stream is recovered intact

•Note - The spread sequences actually shown are icons, not accurate or to scale

Shipping and Receiving” via CDMA



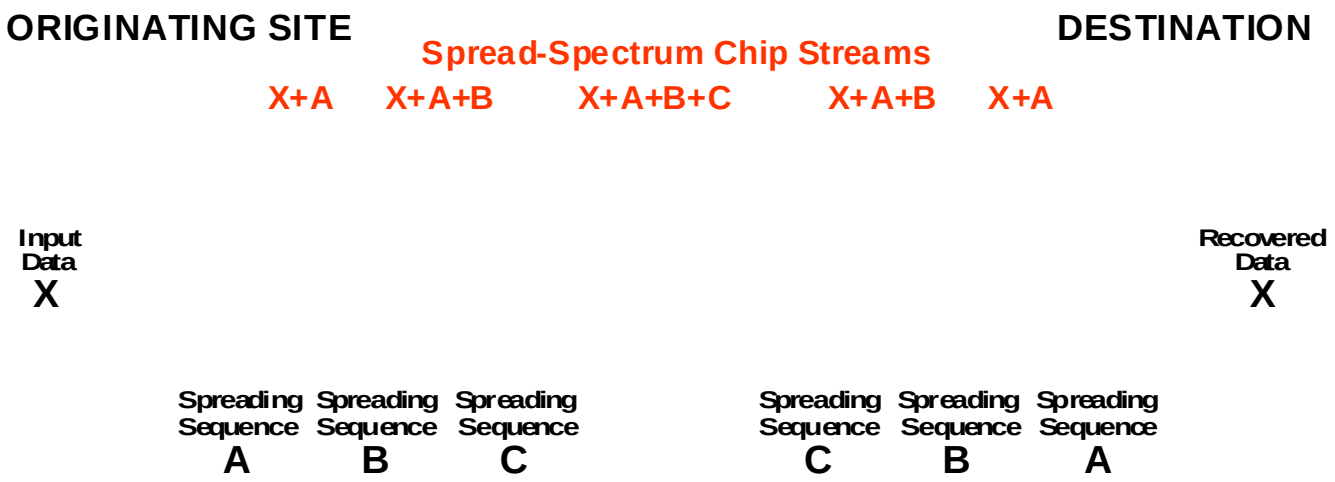
Whether in shipping and receiving, or in CDMA, packaging is extremely important!

Cargo is placed inside “nested” containers for protection and to allow addressing.

The shipper packs in a certain order, and the receiver unpacks in the reverse order.

CDMA “containers” are spreading codes.

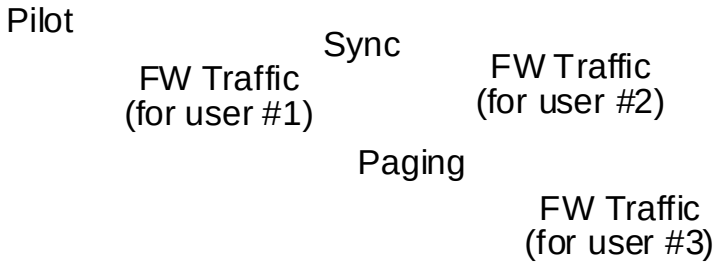
CDMA Spreading Principle: Multiple Successive Spreadings are Reversible



- Multiple spreading sequences can be applied in succession and then reapplied in opposite order, to recover the original un-spread data stream
  - the spreading sequences can have different desired properties
- All spreading sequences originally used must be available in proper synchronization at the recovering destination

Note - The spread sequences actually shown are icons, not accurate or to scale

How Many Spreading Sequences Do We Need? (Discriminating Among Forward Code Channels



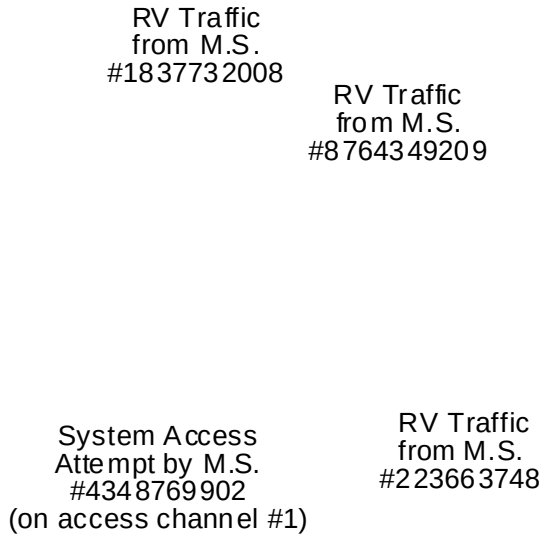
- A Mobile Station, tuned to a particular CDMA frequency, receives a Forward CDMA Channel from a sector in a Base Station.
- This Forward CDMA Channel carries a composite signal made of up to 64 "forward code channels"
- Some of these code channels are "traffic channels" while other are "overhead channels" needed by the CDMA system to operate properly.
- A set of 64 mathematical codes is needed to differentiate the 64 possible forward code channels that can be contained in a Forward CDMA Channel.
  - The codes in this set are called ***"Walsh Codes"***

How Many Spreading Sequences Do We Need? (Discriminating Among Base Station



- A mobile Station is surrounded by Base Stations, all of them transmitting on the same CDMA Frequency
- Each Sector in each Base Station is transmitting a CDMA Forward Traffic Channel containing up to 64 distinct forward code channels
- A Mobile Station must be able to discriminate between different Sectors of different Base Stations and listen to only one set of code channels
- Two binary digit sequences called the ***I and Q Short PN Sequences (or Short PN Codes)*** are defined for the purpose of identifying sectors of different base stations
- These Short PN Sequences can be used in 512 different ways in a CDMA system. Each one of them constitutes a mathematical code which can be used to identify a particular sector of a particular base station

How Many Spreading Sequences Do We Need? (Discriminating Among Reverse Code Channels



- The CDMA system must be able to uniquely identify each Mobile Station that may attempt to communicate with a Base Station
- A very large number of Mobile Stations will be in the market
- One binary digit sequence called the ***Long PN Sequence (or Long PN Code)*** is defined for the purpose of uniquely identifying each possible reverse code channel
- This sequence is extremely long and can be used in trillions of different ways. Each one of them constitutes a mathematical code which can be used to identify a particular user (and is then called a User Long Code) or a particular "access channel" (explained later in this course)

CDMA Magic Spreading Tool #1: Walsh Codes

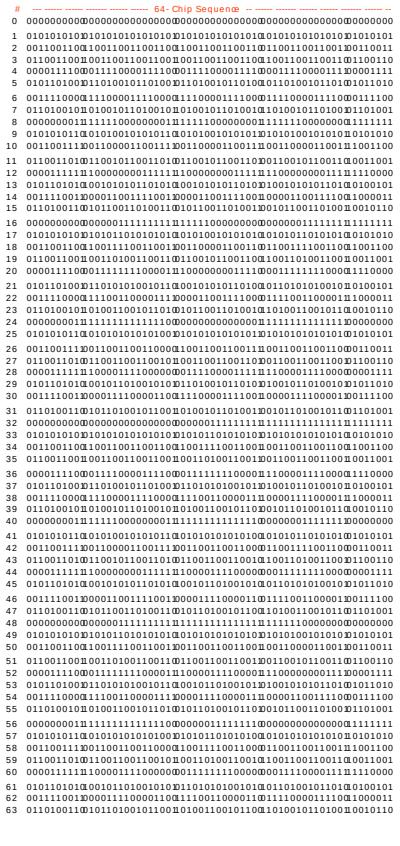
- 64 “Magic” Sequences, each 64 chips long
  - a chip is a binary digit (0 or 1)
- Each Walsh Code is Orthogonal to all other Walsh Codes
  - this means that it is possible to recognize and therefore extract a particular Walsh code from a mixture of other Walsh codes which are “filtered out” in the process
- Two same-length binary strings are orthogonal if the result of XORing them has the same number of 0s as 1s

EXAMPLE:

Correlation of Walsh Code #23 with Walsh Code #59

```
#23   0110100101101001100101101001011010011010110100101100101101001011001
#59   0110011010011001100110010110100101100110100101100110100101100110100
XOR   0000111111110000000011111111000011110000000001111111110000000001111
```

Correlation Results: 32 1’s, 32 0’s: Orthogonal!!



Note: Example of orthogonality – The coordinates used to describe the position of a mobile station at a certain time: latitude (North or South of the Equator), longitude (East or West of Greenwich), altitude (relative to sea level), and time. A change in any of these magnitudes does not affect the other three, therefore they are “orthogonal”.

Correlation and Orthogonality

Correlation is a measure of the similarity between two binary strings

```
  Code #23  01101001011010011001011010010110011010010110100110010110100101 10
-(Code #23) 10010110100101100110100101101001100101101001011001101001011010 01
  Code #59  01100110100110011001100101100110100110010110011001100110100110 01
```

#23	#59	#23
#23	#23	-(#23)
	-(#23)	
PARALLEL	**ORTHOGONAL**	**ANTI-PARALLEL**
XOR: all 0s	XOR: half 0s, half 1s	XOR: all 1s
Correlation: 100% (100% match)	Correlation: 0% (50% match, 50% no-match)	Correlation: -100% (100% no-match)

CDMA Magic Spreading Tool #2: The Short PN Sequences

- The two PN Sequences, I and Q, are 32,768 chips long
  - Together, they can be considered a two-dimensional binary "vector" with distinct I and Q component sequences, each 32,768 chips long
- Each Short PN Sequence (and, as a matter of fact, any sequence) correlates with itself perfectly if compared at a timing offset of 0 chips
- Each Short PN Sequence is special: Nearly orthogonal to a copy of itself that has been offset by any number of chips (other than 0)

32,768 chips long
26 $^{2}/_{3}$ ms.
(75 repetitions in 2 sec.)

I
Q

Unique Properties:

Short PN Sequence vs. Itself @ 0 Offset

I
Q
I
Q

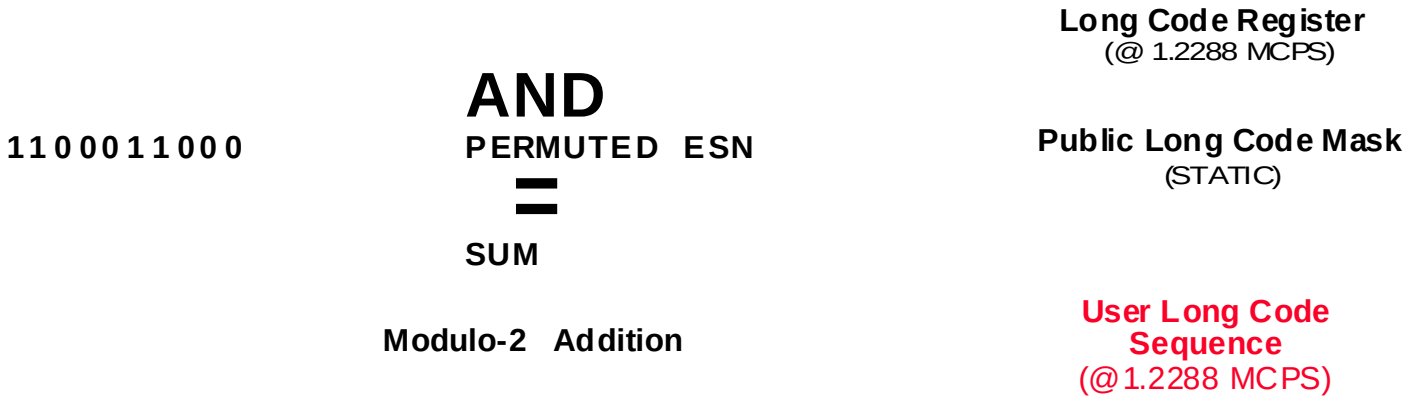
100% Correlation: All bits = 0

Short PN Sequence vs. Itself @ Any Offset

I
Q
I
Q

Orthogonal: 16,384 1's + 16,384 0's

CDMA Magic Spreading Tool #3: The Long PN Sequence (User Long Code)



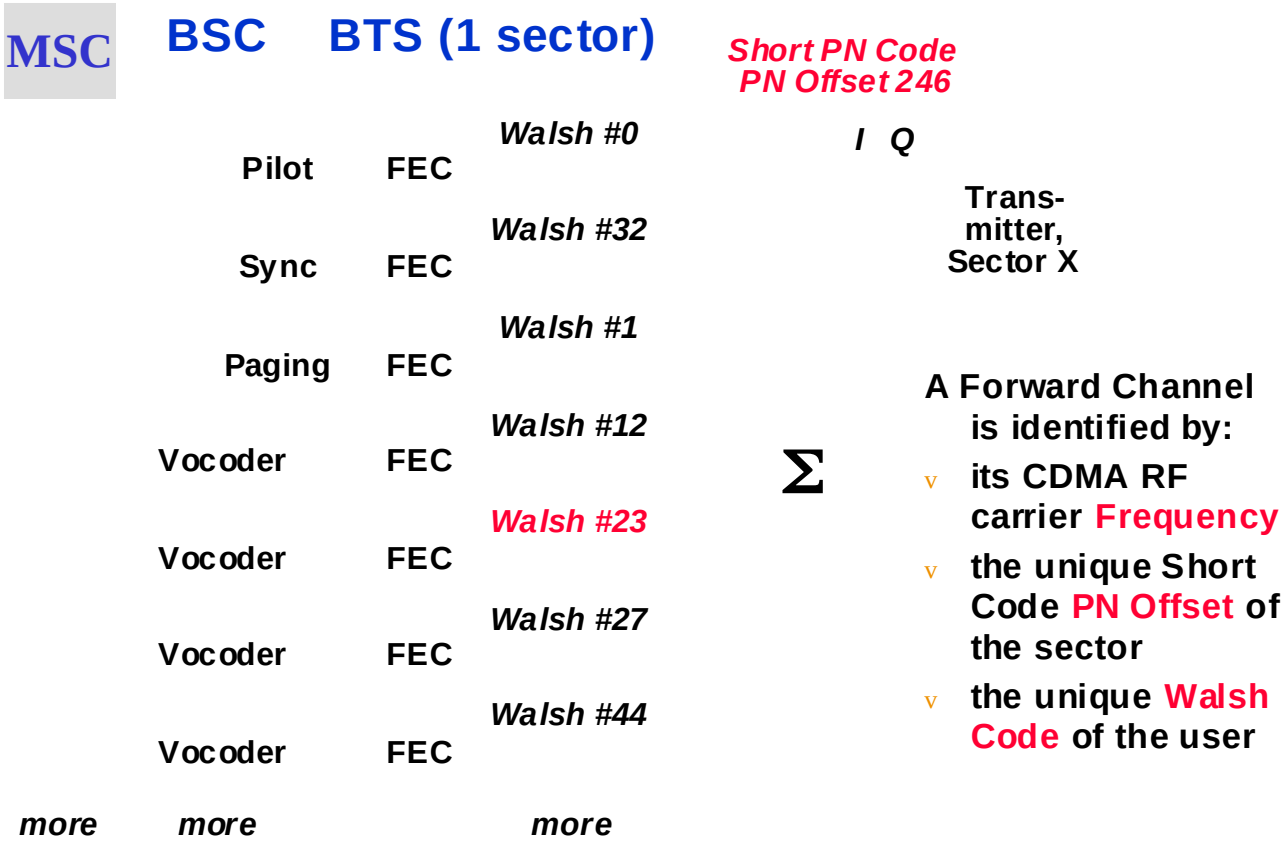
- Each mobile station uses a world-unique User Long Code Sequence generated by applying a mask, based on its 32-bit ESN, to the 42-bit Long Code Generator which was synchronized with the CDMA system during the mobile station initialization
- Generated at 1.2288 Mcps, this sequence requires 41 days, 10 hours, 12 minutes and 19.4 seconds to complete
- Portions of the Users Long Codes generated by different mobile stations for the duration of a call are not exactly orthogonal but are sufficiently different to permit reliable decoding on the reverse link

CDMA Code Channels in the Forward Direction

Pilot	Walsh 0
Paging	Walsh 1
	Walsh 6
	Walsh 11
	Walsh 19
	Walsh 20
Sync	Walsh 32
	Walsh 37
	Walsh 41
	Walsh 42
	Walsh 55
	Walsh 56
	Walsh 60

- **PILOT: WALSH CODE 0**
  - The Pilot is a "structural beacon" which does not contain a character stream. It is a timing source used in system acquisition and as a measurement device during handoffs
- **SYNC: WALSH CODE 32**
  - This carries a data stream of system identification and parameter information used by mobiles during system acquisition
- **PAGING: WALSH CODES 1 up to 7**
  - There can be from one to seven paging channels as determined by capacity needs. They carry pages, system parameters information, and call setup orders
- **TRAFFIC: anyremaining WALSH codes**
  - The traffic channels are assigned to individual users to carry call traffic. All remaining Walsh codes are available, subject to overall capacity limited by noise

Coding Process on CDMA Forward Code Channels



CDMA Code Channels in the Reverse Direction

There are two types of CDMA Reverse Channels:

- **TRAFFIC CHANNELS** are used by individual users during their actual calls to transmit traffic to the BTS
  - a reverse traffic channel is defined by a user-specific public or private Long Code mask
  - there are as many reverse Traffic Channels as there are CDMA phones in the world

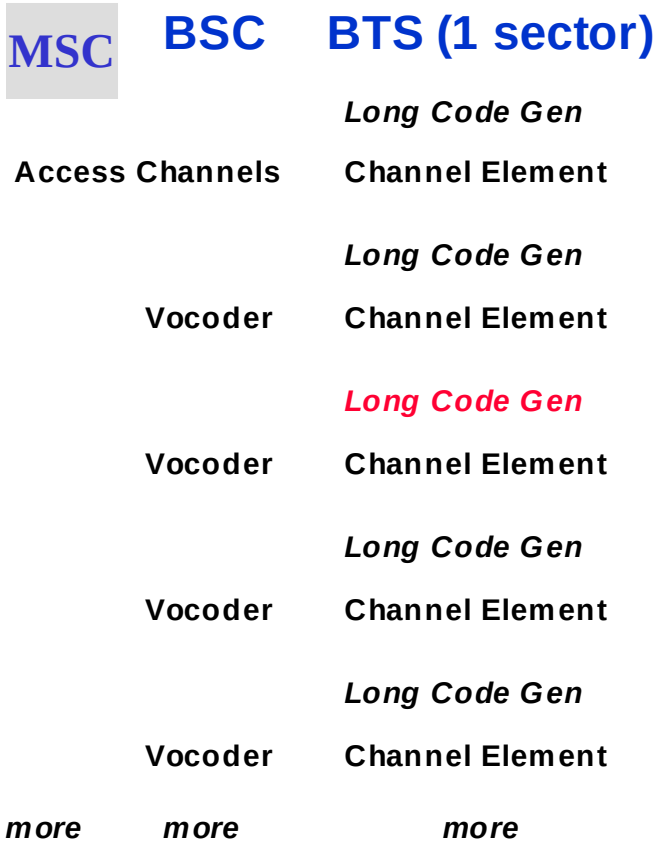
BTS

- **ACCESS CHANNELS** are used by mobile stations not yet in a call to transmit registration requests, call setup requests, page responses, order responses, and other signaling information
  - an access channel is defined by a user-independent public long code mask
  - Access channels are paired with Paging Channels. There can be up to 32 access channels per paging channel

REG

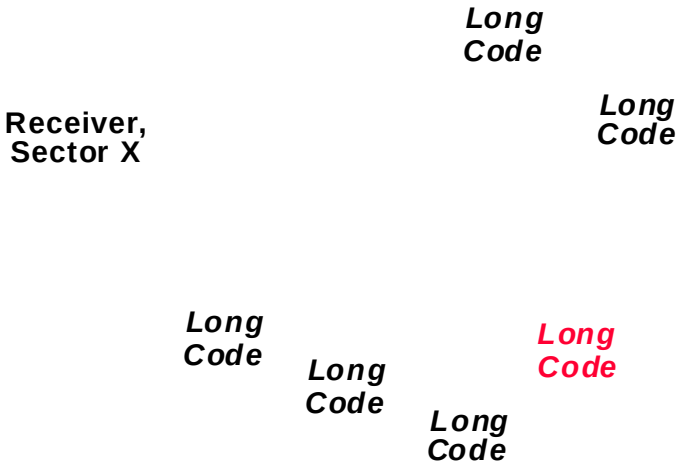
1-800
242
4444

Coding Process on CDMA Reverse Code Channels



A Reverse Channel is identified by:

- its CDMA RF carrier **Frequency**
- the unique **Long Code PN Offset** of the individual handset



CDMA's "Magic" Spreading Sequences Summary of Characteristics & Functions

- Each CDMA spreading sequence is used for a specific purpose on the forward link and a different purpose on the reverse link
- The sequences are used to form "code channels" for users in both directions

Cell



64 chips long

64 codes

32,768 chips long
26-2/3 ms.
(75 repetitions in 2 sec.)

I
Q

AND
=

Modulo-2 Addition

Type of Sequence	How Many	Length	Special Properties	Forward Link Function	Reverse Link Function
Walsh Codes	64	64 chips 1/19,200 sec.	Mutually Orthogonal	User identity within cell's signal	Information Carrier super-reliable "Trojan horse"
Short PN Sequences	2	32,768 chips 26-2/3 ms 75x in 2 sec.	Near orthogonal with itself at any chip offset except 0	Distinguish Cells, Sectors & Quadrature Spreading	Quadrature Spreading (Zero offset)
Long PN Sequence	1	2^{42} chips ~41 days	sections of it are near-orthogonal	Data Scrambling to avoid all 1's or 0's	Data Scrambling & Distinguish users

Basic Spreading & De-spreading Example: User's Data Spread, Sent, Recovered

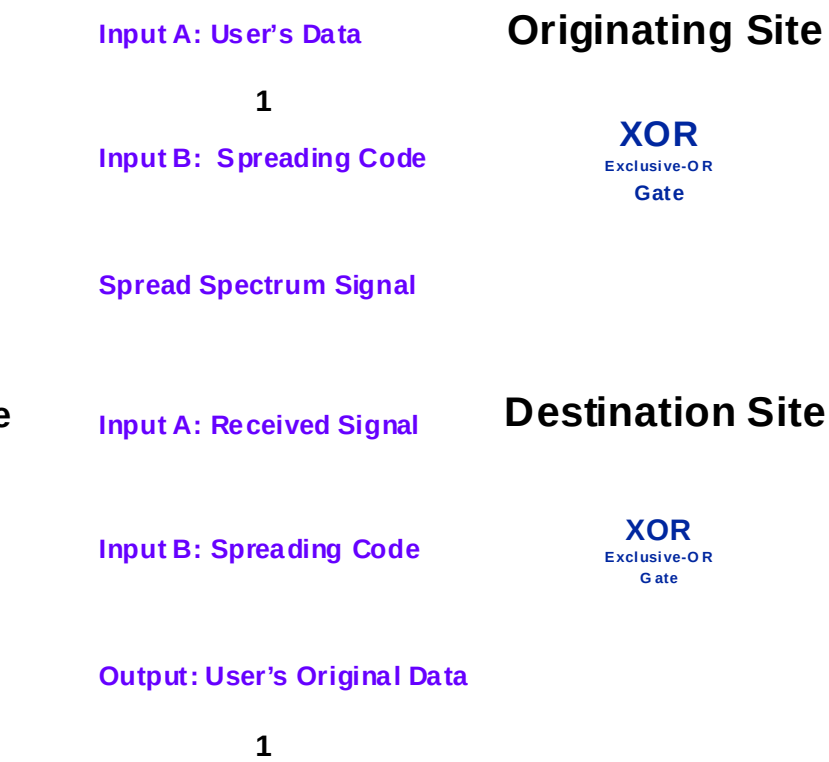
At Originating Site:

- Input A: User's Data @ 19,200 bits/second
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: Spread spectrum signal

via air interface

At Destination Site:

- Input A: Received spread spectrum signal
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: User's Data @ 19,200 bits/second just as originally sent



Drawn to actual scale and time alignment

Spectrum Usage and System Capacity: Signal Bandwidth, Vulnerability, and Frequency Reuse

- Each wireless technology (AMPS, NAMPS, D-AMPS, GSM, CDMA) uses a specific modulation type with its own unique signal characteristics
- The total traffic capacity of a wireless system is determined largely by radio signal characteristics and RF design
- RF signal vulnerability to Interference dictates how much interference can be tolerated, and therefore how far apart same-frequency cells must be spaced
- For a specific S/N level, the Signal Bandwidth determines how many RF signals will "fit" in the operator's licensed spectrum

$$17 \text{ dB} = 10^{1.7} \cong 50$$
$$14 \text{ dB} = 10^{1.4} \cong 25$$
$$12 \text{ dB} = 10^{1.2} \cong 16$$

AMPS, D-AMPS, N-AMPS

1 3 1 Users

7 2 3 4

Vulnerability: C/I ≅17 dB

30 30 10 kHz

Typical Frequency Reuse N=7

GSM

8 Users

Vulnerability: C/I ≅12-14 dB

2 3 4

200 kHz

Typical Frequency Reuse N=4

CDMA

Vulnerability: E_b/N_o ≅6 dB

1250 kHz

Typical Frequency Reuse N=1

Relationship Between E_b/N_0 And S/N

$$E_b = \frac{\text{Signal Power}}{\text{Bit Rate}} = \frac{S}{R} = \frac{E/t}{B/t} \qquad N_0 = \frac{\text{Noise Power}}{\text{Bandwidth}} = \frac{N}{W}$$

Signal to Noise

$$\frac{E_b}{N_0} = \frac{\frac{S}{R}}{\frac{N}{W}} = \frac{S}{R} \times \frac{W}{N} = \frac{S}{N} \times \frac{W}{R}$$

Processing Gain

8 Kb vocoder (Full Rate)

$$\frac{W}{R} = \frac{1{,}250{,}000}{9{,}600} = 130 = 10^{2.11} = 21\ dB$$

13 Kb vocoder (Full Rate)

$$\frac{W}{R} = \frac{1{,}250{,}000}{14{,}400} = 87 = 10^{1.94} = 19\ dB$$

CDMA Advantage (13 kb vocoder at full rate)

Signal to Noise
Processing Gain ($^{W}/_{R}$)
E_b N_0

$$\frac{S}{N} \times 10^{1.9} = 10^{0.6} \quad \text{so} \quad \frac{S}{N} = \frac{10^{0.6}}{10^{1.9}} = 10^{-1.3} = -13\ \text{dB}$$

Tech-nology	Modulation Type	Channel Bandwidth	Quality Indicator	S/N
AMPS	Analog FM	30 KHz.	C/I ≅17 dB	S/N ≅17 dB
N-AMPS	Analog FM	10 KHz.	C/I ≅17 dB	S/N ≅17 dB
D-AMPS	DQPSK	30 KHz.	C/I ≅17 dB	S/N ≅17 dB
GSM	GMSK	200 KHz.	C/I ≅12-14 dB	S/N ≅12 to 14 dB
CDMA	QPSK/OQPSK	1,250 KHz.	E_b/N_o ≅6dB	S/N ≅–13 dB

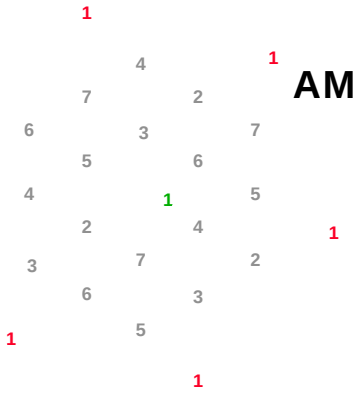
17 dB = $10^{1.7}$ ≅50
14 dB = $10^{1.4}$ ≅25
12 dB = $10^{1.2}$ ≅16

$-13\ \text{dB} = 10^{-1.3} \cong 0.05$

Reverse Link Interference Scenarios

- AMPS, N-AMPS, TDMA, and GSM systems do not use spreading. Co-channel users must be separated by distance to achieve the desired C/I ratio.
  - Interferors are co-channel users in distant cells
- CDMA systems use spreading and due to their spreading gain can tolerate negative C/I.
  - Many co-channel users can share the *same cell*!
  - However, this requires that all users be power-controlled so their signals reach the base station at the same signal level

Tight Reverse-Link Power Control is *essential* in CDMA

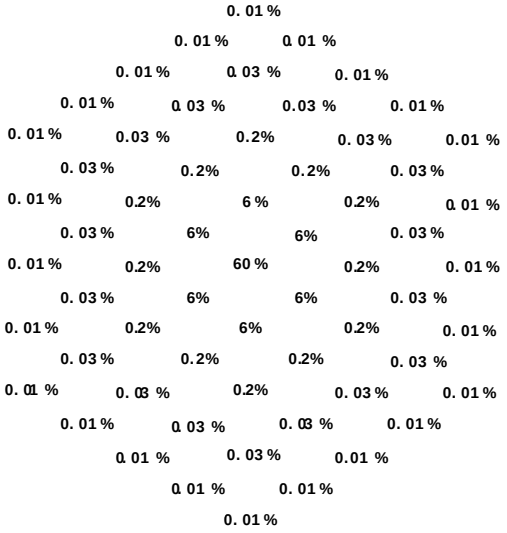


AMPS-TDMA-GSM

CDMA

users

CDMA Capacity Considerations



URBAN AREA

1 X 60 = 60

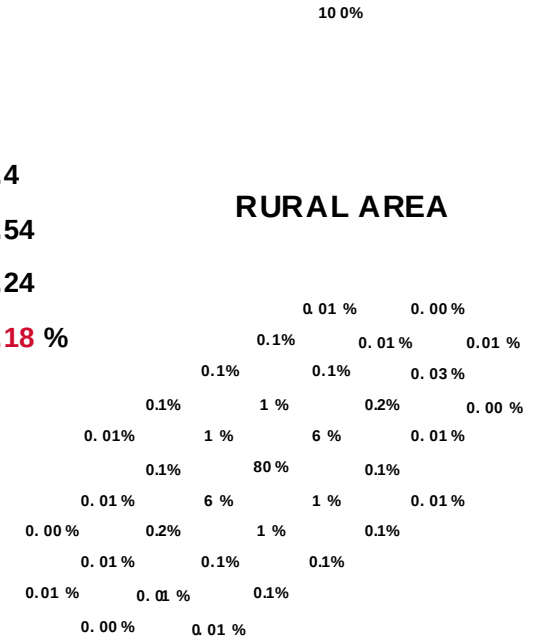
6 X 6 = 36

12 X 0.2 = 2.4

18 X 0.03 = 0.54

24 X 0.01 = 0.24

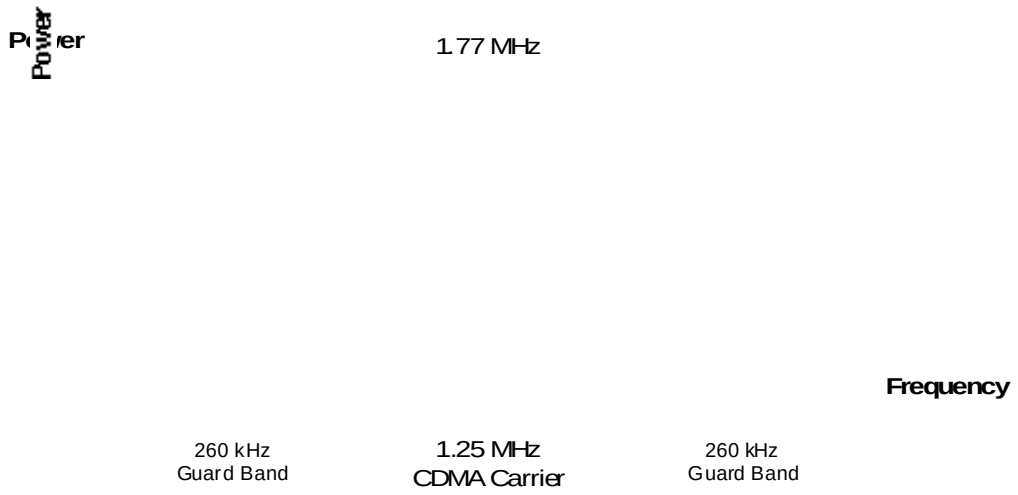
TOTAL = 99.18 %



RURAL AREA

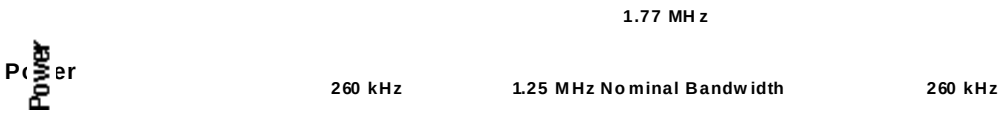
NEAR A HIGHWAY

Coexistence of CDMA with Other Systems



- Guard bands are needed between CDMA and other systems because CDMA increases the noise floor for those systems.
- These systems appear as noise for the CDMA system.
- No guard band is needed between adjacent CDMA systems.

Overlaying CDMA on an AMPS System



1770 ÷ 30 = 59

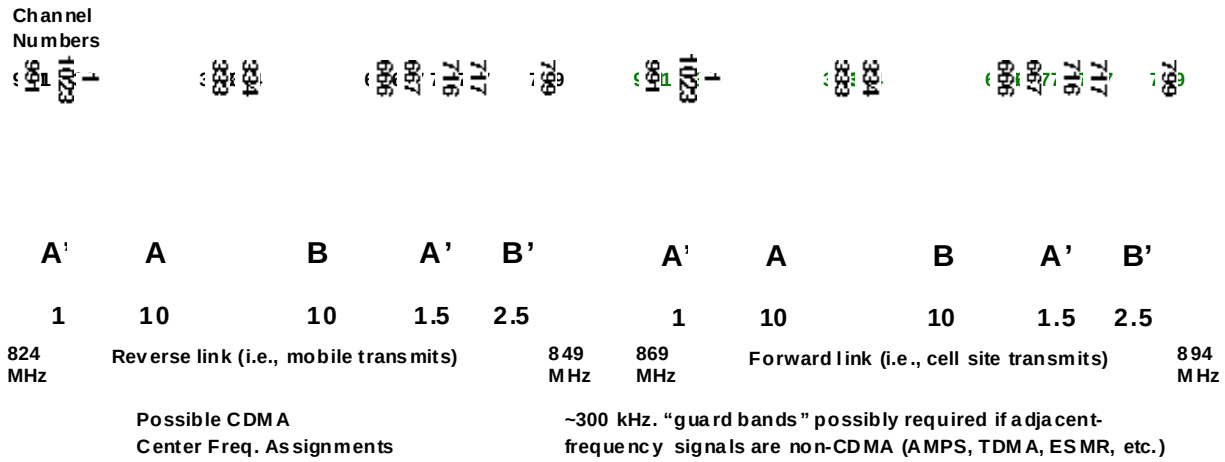
1250 ÷ 30 = 41.7

260 ÷ 30 = 8.7

CDMA

- All frequencies are available for AMPS use
- Only the frequencies in the purple area are available for AMPS use

CDMA 800 MHz Cellular Spectrum Usage



- All CDMA RF carriers are 1.25 MHz. wide
  - can serve ~22 users w/8 kb vocoder (~17 users w/13 kb vocoder)
- The cellular spectrum of one operator is 12.5 MHz. wide. You'd expect that 10 CDMA carriers would fit. However, only 9 carriers can be used
  - operators must maintain a "token" AMPS presence for several years
  - "guard bands" are required at the edges of frequency blocks or any frequency boundaries between CDMA/non-CDMA signals
  - no guard bands are required between adjacent CDMA carriers

CDMA 800 MHz Cellular Spectrum Usage

Order	Side “A”	Side “B”
1	283	384
2	242	425
3	201	466
4	160	507
5	119	548
6	78	589
7	37	630
8	1019	777
9	691	736

The above table is an example of CDMA channel allocation, in chronological order, which allows maximum CDMA channel packing.

Note: a) requires frequency coordination with non-cellular interferes

b) requires frequency coordination with A-side carrier

Deploying CDMA on the 1900 MHz band



CDMA CARRIER

Frequency

1770 ÷ 50 = 35.4

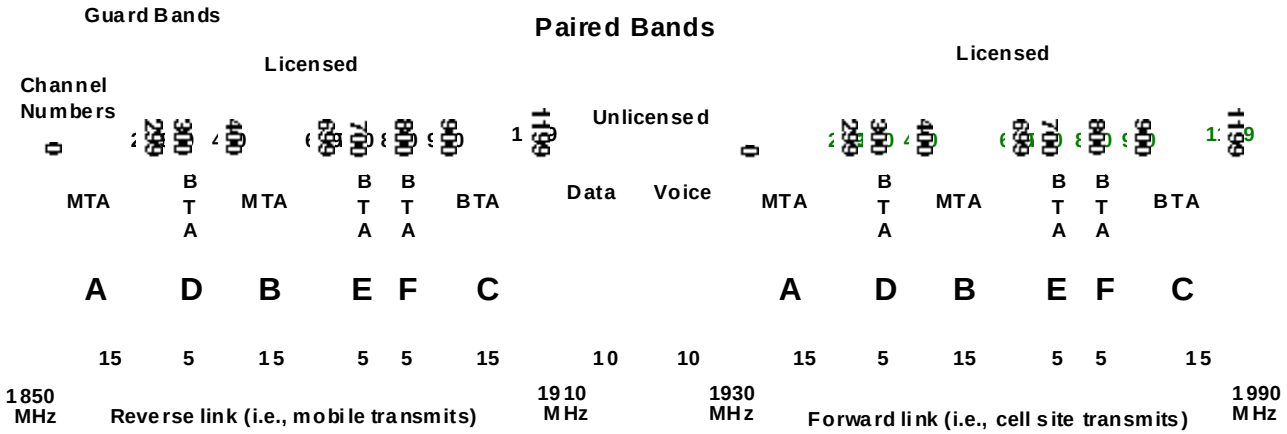
1250 ÷ 50 = 25

260 ÷ 50 = 5.2

CDMA

- **All frequencies are available for non-CDMA use**
- **Only the frequencies in the blue area are available for non CDMA use**

CDMA PCS 1900 MHz Spectrum Usage



- A, B, and C licenses can accommodate 11 CDMA RF channels in their 30 MHz of spectrum
- D, E, and F licenses can accommodate 3 CDMA RF channels in their 10 MHz of spectrum
- 260 kHz guard bands are required on the edges of the PCS spectrum to ensure no interference occurs with other applications just outside the spectrum

CDMA PCS 1900 MHz Spectrum Usage

PCS Band A

1	25
2	50
3	75
4	100
5	125
6	150
7	175
8	200
9	225
10	250
11	275

493 **BTAs** (Basic Trading Areas) are grouped into 51 **MTAs** (Metropolitan Trading Area s).

The following tables are examples of CDMA channel allocation, in chronological order, which allow maximum CDMA channel packing. Each table represents the “preferred” set of CDMA channels according to J-STD-008.

1	25
2	50
3	75
4	100
5	125
6	150
7	175
8	200
9	225
10	250
11	275

PCS Band B

1	25
2	50
3	75
4	100
5	125
6	150
7	175
8	200
9	225
10	250
11	275

PCS Band C

1	325
2	350
3	375

PCS Band D

1	725
2	750
3	775

PCS Band E

1	825
2	850
3	875

PCS Band F

Sources

- Vijay K. Garg, “Wireless Network Evolution: 2G to 3G”, 2002, Prentice Hall, ISBN: 0130280771
- Scott Baxter, www.howcdmaworks.com/

End of Lesson