

# 2G Cellular Telephony

## Zero Generation System (1975 – 1990)

**3 kHz voice bandwidth (like POTS)**

**Frequency Division Multiple Access (FDMA)**

Analog FM modulation

Total bandwidth divided into hundreds of channels

**Full duplex transmission**

2 frequencies per telephone during call

Dedicated Base Station (BS) transmission frequency (uplink)

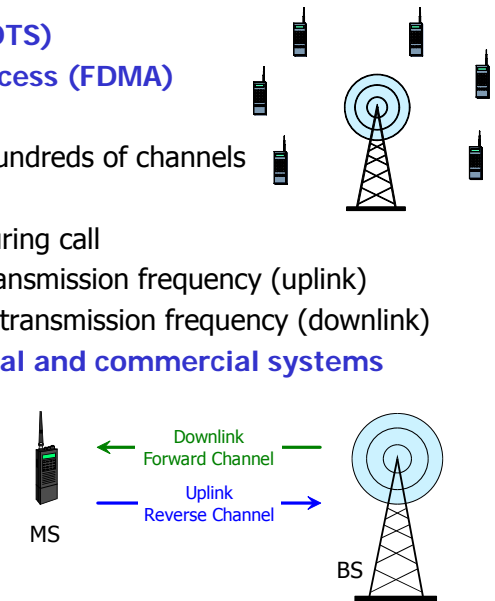
Dedicated Mobile Station (MS) transmission frequency (downlink)

**Various non-compatible national and commercial systems**

2G systems evolved from

US AT&T AMPS

British Telecom TACS



## 1G — Advance Mobile Phone Systems (AMPS)

**North American first generation analog system — IS-553**

**25 MHz transmission band per direction**

20 MHz frequency band per direction (1976)

Mobile Station (uplink): 825 - 845 MHz

Base Station (downlink): 870 - 890 MHz

Additional 5 MHz band per direction (1986)

Mobile Station (uplink): 845 - 849 MHz

Base Station (downlink): 890 - 895 MHz

**Frequency Division Multiple Access (FDMA)**

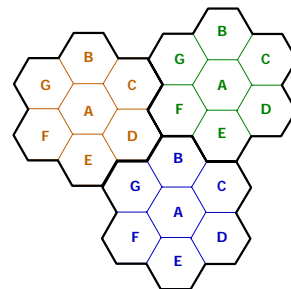
Divide band into 30 kHz RF voice channels

$$\frac{25 \text{ MHz per cluster}}{30 \text{ kHz per channel}} = 832 \text{ channels per cluster}$$

**7 cell frequency reuse pattern (A, B, ..., G)**

832 channels / 7 cells < 118 channels per cell

Typically 90 useful channels per cell



## Commercial Diversity (Competition)

**Split 25 MHz band for 2 service providers**

B band for the established Telco

A band for a second cellular operator

832 channels / 2 bands = 416 channels per service provider

118 channels per cell / 2 bands < 59 channels per cell per provider

| Band | Frequency Range (MHz)       | Use                      |
|------|-----------------------------|--------------------------|
| A    | 824 to 835 and 845 to 846.5 | MS: Transmit from mobile |
|      | 869 to 880 and 890 to 891.5 | BS: Receive at mobile    |
| B    | 835 to 845 and 846.5 to 849 | MS: Transmit from mobile |
|      | 880 to 890 and 891.5 to 894 | BS: Receive at mobile    |

## AMPS Digital Call Control

### AMPS similar to POTS

- Most channel capacity allocated to voice
- Limited call control

### Call control channel

- 10 kbps FSK (digital FM)
- Registration
- Authentication
- Operations, Administration, Maintenance (OAM)

### Control information

- From phone
  - Mobile Identification Number (10 digit phone number)
  - Electronic Serial Number (32-bit ID of telephone)
  - Home System Identification (15-bit provider code)
- From network
  - Frequencies available to phone

## Total Access Communications System (TACS)

### British first generation analog standard

#### 25 MHz transmission band

- MS (uplink): 890 - 915 MHz
- BS (downlink): 935 - 960 MHz
- Not compatible with AMPS

#### 25 kHz per channel

- 25 MHz per cluster / 25 kHz per channel = 1000 channels per cluster

#### 7 cell reuse pattern

- 1000 channels / 7 cells = 140 channels per cell

## Second Generation Systems

### 2G Analog systems

- Triple number of channels per cell
- Motorola proprietary products
  - Narrowband Advance Mobile Phone Systems (N-AMPS)
  - Motorola Integrated Radio System (MIRS)

### Time Division Multiple Access (TDMA)

- Divide FDMA radio channel into time slots
- MS transmits digitized voice in one time slot on one frequency
- North American d-AMPS
- European GSM

### Code Division Multiplex Access (CDMA)

- Create orthogonal binary digital transmission codes
- MS transmits in one code on one frequency

## Narrowband AMPS (N-AMPS)

### Based on AMPS standard

- Developed by Motorola

### Allocate 10 kHz per channel — instead of 30 kHz in AMPS

- Tripled number of channels
- Combines data compression and lower voice quality

### First standard Short Message Service (SMS)

- Alphanumeric characters in control channel

### Standards

- N-AMPS is IS-88, 89, 90
- Combined with AMPS as IS-91

## Review of E1 Time Division Multiplexing (TDM)

### Analog voice channel (300 Hz to 3300 Hz)

Sampled at 8000 samples/second  
Round-off to 1-byte sample

### Digital voice bit stream (DS-0)

$$\frac{8000 \text{ samples}}{\text{second}} \times \frac{8 \text{ bits}}{\text{sample}} = 64 \text{ kbps}$$

### E1 frame contains 32 bytes

1 byte each from 30 DS-0 streams  
2 control bytes

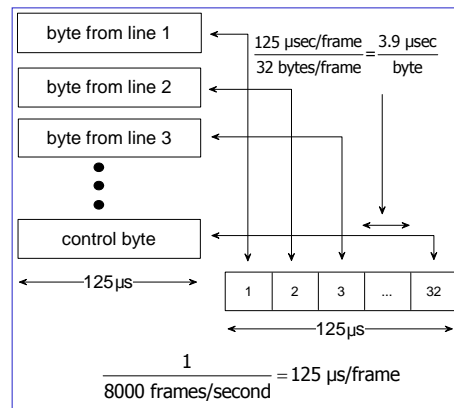
### Isochronous real time

1 byte sample every 125  $\mu\text{sec}$

32 bytes per frame

E1 bit rate =  $32 \times 64 \text{ kbps} = 2.048 \text{ Mbps}$

Squeeze 125  $\mu\text{sec}$  sample into 125  $\mu\text{sec} / 32 = 3.9 \mu\text{sec}$  transmission time



## Digital AMPS (d-AMPS)

### North American 2G digital cellular on AMPS infrastructure

AMPS-based FDMA

$$\frac{25 \text{ MHz per cluster}}{30 \text{ kHz per voice channel}} = 832 \text{ voice channels per cluster}$$

### Digital transmission

Transmit 48,600 bps in each 30 kHz voice channel

Voice channel modulation — DQPSK (encoded PSK)

Control channel modulation — AMPS compatible FSK

### Time Division Multiple Access (TDMA)

Divide each voice channel into 6 time slots

Allocate 2 time slots per user

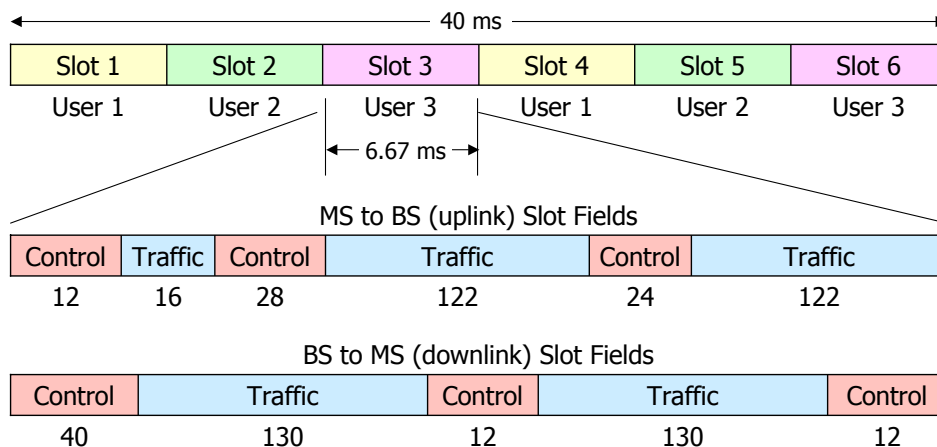
3 users per voice channel

48,600 bps per channel / 3 users per channel = 16,200 bps per user

### Standards

IS-54 replaced by IS-136

## d-AMPS Digital Frames



### Time slot contains

260 traffic bits (digitized voice)

64 control bits (call control, synchronization, OAM)

## d-AMPS Data Rates

### Slot width

260 data bits + 64 control bits = 324 bits per slot

### Frame size

324 bit per slot  $\times$  6 slots per frame = 1,944 bits per frame

### Frame and slot rates

40 ms per frame / 6 time slots per frame = 6.67 ms per time slot

40 ms per frame  $\Rightarrow$  25 frames per second

### Total transmission rate

25 frames per second  $\times$  1,944 bits per frame = 48,600 bps

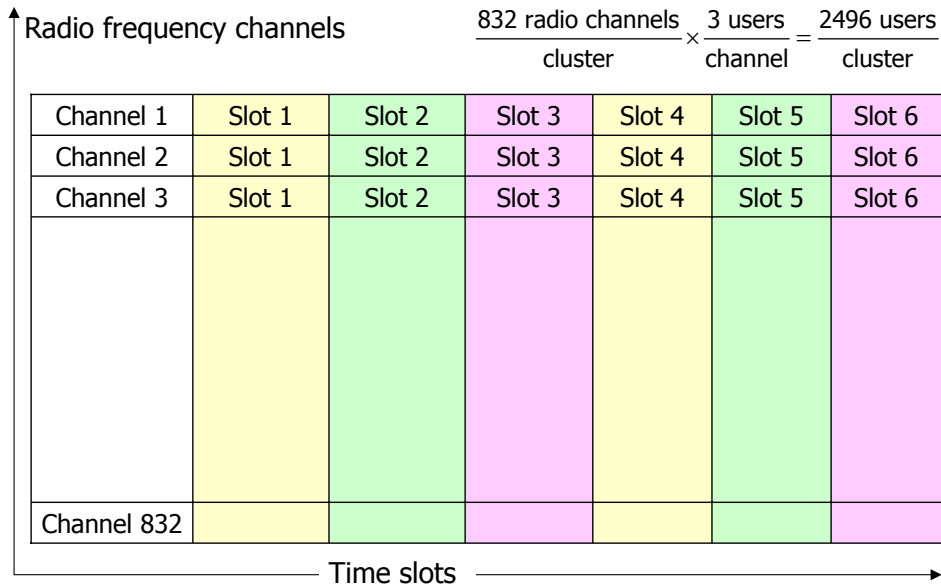
### User rates

$$\frac{25 \text{ frames}}{\text{second}} \times \frac{2 \text{ user slots}}{\text{frame}} \times \frac{260 \text{ traffic bits}}{\text{user slot}} = 13,000 \text{ bps (user traffic rate)}$$

$$\frac{25 \text{ frames}}{\text{second}} \times \frac{2 \text{ user slots}}{\text{frame}} \times \frac{64 \text{ control bits}}{\text{user slot}} = 3,200 \text{ bps (user control rate)}$$

total user rate = 16,200 bps

## d-AMPS Channels



## Voice Encoding

### Analog to digital

Vector Sum Excited Linear Prediction

Generates 159-bit sample every 20 ms

Data rate = 159 bits / 20 ms = 7,950 bps

### Forward error correction (protection)

Encoding permits error correction at receiver

77 most significant speech bits encoded to 178 bits

159 - 77 = 82 less significant bits not encoded

Encoded data = 178 + 82 bits = 260 bits

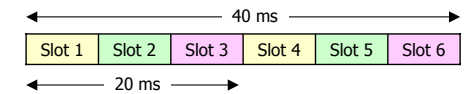
260 bits / 20 ms = 13,000 bps

### User time slots

Transmit frame every 40 ms

Frame contains two time slots per user

Time slot contains 260-bit digitized 20 ms voice sample



## GSM

### Global System for Mobile Communications

European Union 2G digital cellular on TACS frequencies

### Non-TACS channelization

Divide band into 200 kHz RF channels (8 TACS voice channels)

25 MHz per cluster / 200 kHz per channel = 125 channels per cluster

### Digital transmission

Transmit 270.883 kbps in each 200 kHz radio channel

Voice and control modulation

Gaussian minimum-shift keying (GMSK) — optimized FSK

### Time Division Multiple Access (TDMA)

Divide each channel into 8 time slots

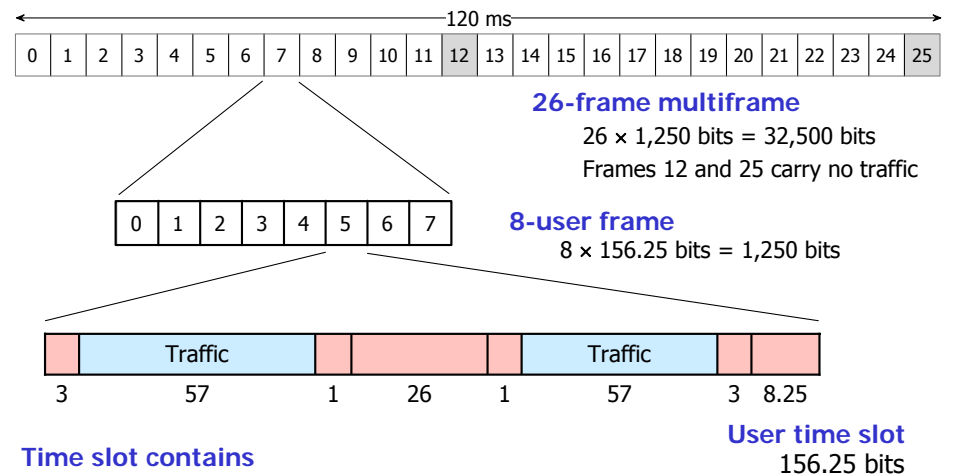
Allocate 1 time slot per user

270.883 kbps per channel / 8 users per channel = 33,086 bps per user

### Standards

European Telecommunications Standards Institute (ETSI)

## GSM Digital Frames



### Time slot contains

57 + 57 = 114 traffic bits (digitized voice or data)

42.25 control bits for call control, synchronization, OAM

8.25-bit field — variable no-transmission interval between frames

Total bits in time slot = 114 + 42.25 = 156.25

## GSM Data Rates

### Time slot width

114 traffic bits + 42.25 control bits = 156.25 bits

### Frame width

8 time slots per frame × 156.25 bits per slot = 1,250 bits per frame

### Multiframe width

26 frames × 1,250 bits per frame = 32,500 bits per multiframe

### Total transmission rate

32,500 bits per multiframe / 120 ms = 270.833 kbps

### User traffic rate

Traffic in 24 frames — frames 12 and 25 carry no traffic

$$\left( \frac{2 \times 57 \text{ bits}}{\text{time slot}} \times \frac{24 \text{ time slots}}{\text{multiframe}} \right) / \frac{120 \text{ ms}}{\text{multiframe}} = 22.8 \text{ kbps}$$

## GSM Voice Encoding

### A/D conversion

Analog voice signal filtering at 3.3 kHz

Sampling at 8000 samples / second

Rounded off to 13-bit quantization ( $2^{13}$  level encoding)

8000 samples/second × 13-bits/sample = 104 kbps

### Voice Encoding

Regular Pulse Excited Long Term Prediction (RPE-LTP)

8-times voice compression

104 kbps / 8 = 13 kbps compressed data rate

## GSM Voice Error Protection

### Compressed 20 ms sample

Uncompressed sample size = 104 kbps × 20 ms = 2080 bits

Compressed sample size = 13 kbps × 20 ms = 260 bits

### Error protection on most significant bits

260-bit sample → 456-bit protected sample

### Protected sample transmitted in 8 time sequential slots

20 ms sample / 8 slots = 2.5 ms sample per slot

456 bits / 8 time slots = 57 bits per time slot

### 2 × 57-bit traffic fields per time slot

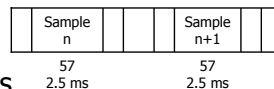
Each time slot holds 1/8 of 2 sequential samples

2 fields per time slot × 2.5 ms per field = 5 ms traffic per time slot

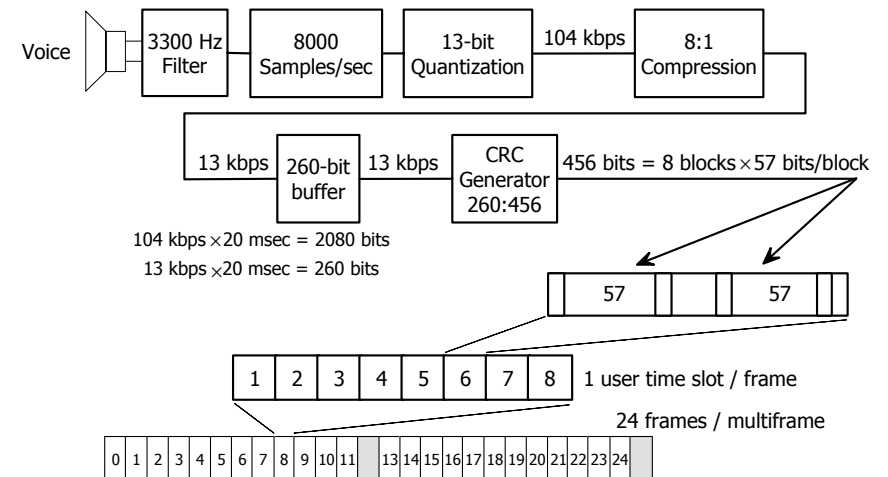
### On large (uncorrectable) error at receiver

Sample replaced with previous sample

Large error in 1 sample worse than small errors in 2 samples



## GSM Voice Transmission Summary



57 user bits per field × 2 fields per frame × 24 frames per multiframe = 2736 user bits per multiframe

2736 bits per multiframe / 120 ms per multiframe = 22.8 kbps

22.8 kbps / (456/260) = 13 kbps

## GSM Transmission Rate vs Service Rate

### 24 user frames serviced in 120 ms multiframe

$$\frac{120 \text{ ms}}{24 \text{ user frames}} = 5 \text{ ms user traffic per frame}$$

### Squeeze 8 user slots into frame transmission time

$$5 \text{ ms user traffic serviced in } \frac{5 \text{ ms}}{8} = 0.625 \text{ ms}$$

### 26 physical frames per multiframe transmission

$$\frac{120 \text{ ms}}{26 \text{ frames}} = \frac{60}{13} \text{ ms per frame} = 4.62 \text{ ms per frame}$$

### Squeeze 8 user slots into physical frame transmission time

$$\frac{60}{13} \text{ ms} \times \frac{1}{8} = \frac{15}{26} \text{ ms} = 0.58 \text{ ms per slot transmission}$$

## Comparing d-AMPS and GSM

| Feature                                 | d-AMPS   | GSM  |
|---|--|--|
| <b>Total bandwidth</b>                  | 25 MHz per direction per cluster   | 25 MHz per direction per cluster   |
| <b>Frequency bands</b>                  | MS (uplink): 825 - 849 MHz<br>BS (downlink): 870 - 895 MHz   | MS (uplink): 890 - 915 MHz<br>BS (downlink): 935 - 960 MHz   |
| <b>Voice encoding</b>                   | 13 kbps (compressed protected)   | 22.8 kbps (compressed protected)   |
| <b>FDM (radio) channels per cluster</b> | $\frac{25 \text{ MHz}}{\text{cluster}} \div \frac{30 \text{ kHz}}{\text{channel}} = \frac{832 \text{ channels}}{\text{cluster}}$         | $\frac{25 \text{ MHz}}{\text{cluster}} \div \frac{200 \text{ kHz}}{\text{channel}} = \frac{125 \text{ channels}}{\text{cluster}}$      |
| <b>Digital capacity per FDM channel</b> | 48.6 kbps per 30 kHz channel   | 270.833 kbps per 200 kHz channel   |
| <b>TDMA (digital) slots per channel</b> | 3 digital voice streams/channel  | 8 digital voice streams/channel  |
| <b>TDMA channels per cluster</b>        | $\frac{832 \text{ channels}}{\text{cluster}} \times \frac{3 \text{ slots}}{\text{channel}} = \frac{2,496 \text{ slots}}{\text{cluster}}$ | $\frac{124 \text{ channels}}{\text{cluster}} \times \frac{8 \text{ slots}}{\text{channel}} = \frac{992 \text{ slots}}{\text{cluster}}$ |
| <b>Protocol Structure</b>               | Simple — comparable to POTS  | Complex — comparable to ISDN   |

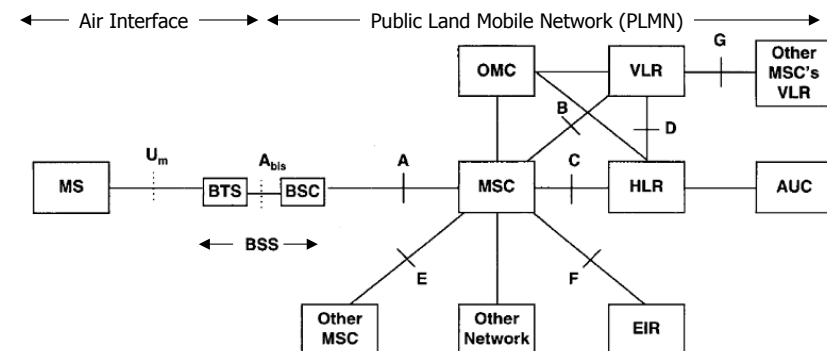
## Comparison of User Slots

|  | d-AMPS  | GSM   | d-AMPS to GSM Ratio |
|--|---|---|---------------------|
| <b>User slots</b>                        | 2496  | 992   | 2.5                 |
| <b>Bits / Hz</b>                         | $48.6 / 30 = 1.62$  | $270.8 / 200 = 1.35$  | 1.2                 |
| <b>Used slots</b>                        | 100%  | $24 / 26 = 92\%$  | 1.08                |
| <b>Traffic / total</b>                   | $260 / 324 = 0.80$  | $114 / 156 = 0.73$  | 1.09                |
| <b>Bits per 20 ms voice sample</b>       | $20 \text{ ms} \times 13 \text{ kbps} = 260 \text{ bits}$ | $20 \text{ ms} \times 22.8 \text{ kbps} = 456 \text{ bits}$ |                     |
| <b>20 ms voice samples per 1000 bits</b> | $1000 / 260 = 3.85$                                       | $1000 / 456 = 2.19$   | 1.75                |

### Breakdown of d-AMPS to GSM user slot advantage

$$1.2 \times 1.08 \times 1.09 \times 1.75 = 2.5$$

## Basic GSM Architecture



|     |   |     |   |
|-----|---|-----|---|
| MS  | Mobile Station  | HLR | Home Location Register  |
| BSS | Base Station Subsystem                                    | VLR | Visitor Location Register   |
| BTS | Base Transceiver Station<br>Radio system for one cell     | AUC | Authentication Center<br>User authentication / encryption keys      |
| BSC | Base Station Controller<br>Controller for one or more BTS | EIR | Equipment Identity Register<br>Hardware ID database (theft control) |
| MSC | Mobile Switching Center                                   | OMC | Operations and Maintenance Center                                   |

## Mobility Management

### Registration

Performed when mobile station (MS) activated in Service Area

### Authentication

Verify authenticity of Mobile Station

### Call Establishment

Performed when the user initiates or receives call

### Handoff (handover)

Performed when MS changes connection point to network

### Security

Protects from fraud and eavesdropping

## GSM Registration Procedure

### MS activated

Scans all possible frequencies

Synchronizes to BS beacon message

Beacon — control frame within larger data frame

MS learns frame timings

### MS initiates registration procedure

Requests registration on control channel

Base station system (BSS) authenticates MS

Checks ID number on SIM (subscriber identity module) card

BSS assigns TMSI (Temporary Mobile Subscriber Identity)

BSS updates VLR against HLR

BSS closes control channel

## GSM Registration

|                          | MS | BTS | BSC | MSC | VLR | HLR |
|--------------------------|----|-----|-----|-----|-----|-----|
| Channel request          | →  |     |     |     |     |     |
| Activation response      |    | ←   |     |     |     |     |
| Activation ACK           |    | →   |     |     |     |     |
| Channel assignment       | ←  |     |     |     |     |     |
| Location update request  | →  |     |     |     |     |     |
| Authentication request   | ←  |     |     |     |     |     |
| Authentication response  | →  |     |     |     |     |     |
| Authentication check     |    |     | ↔   |     |     |     |
| TMSI assignment          | ←  |     |     |     |     |     |
| TMSI ACK                 | →  |     |     |     |     |     |
| Update VLR / HLR entries |    |     |     | ↔   |     |     |
| Channel release          | ←  |     |     |     |     |     |

## GSM Call Establishment

MS Initiated

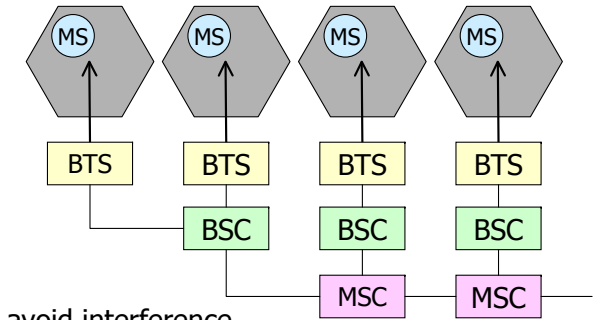
|                            | MS | BTS | BSC | MSC |
|----------------------------|----|-----|-----|-----|
| Request control channel    | →  |     |     |     |
| Assign control channel     | ←  |     |     |     |
| Call establishment request | →  |     |     |     |
| Authentication request     | ←  |     |     |     |
| Authentication response    | →  |     |     |     |
| Encryption key             | ←  |     |     |     |
| Encryption response        | →  |     |     |     |
| Destination address        | →  |     |     |     |
| Routing response           | ←  |     |     |     |
| Traffic channel request    | →  |     |     |     |
| Assign traffic channel     | ←  |     |     |     |
| Available or busy          | ←  |     |     |     |
| Call accepted              | ←  |     |     |     |
| Connection established     |    |     |     |     |
| Data exchange              | →  |     |     |     |

# GSM Call Establishment

Mobile Terminated

|                                | MS | BTS | BSC | MSC | VLR | HLR | GMSC | PSTN | Caller |
|--------------------------------|----|-----|-----|-----|-----|-----|------|------|--------|
| Standard call set-up           |    |     |     |     |     |     |      |      | ←      |
| Request to Gateway MSC         |    |     |     |     |     |     |      | ←    |        |
| HLR user request               |    |     |     |     |     | ↔   |      |      |        |
| Assign roaming number          |    |     |     |     | ↔   |     |      |      |        |
| Request to MSC (user location) |    |     |     |     |     | ←   |      |      |        |
| Update user status             |    |     |     |     | ↔   |     |      |      |        |
| Page MS                        | ←  |     |     | →   |     |     |      |      |        |
| Authentication                 |    |     |     | ↔   |     |     |      |      |        |
| Call connection                | ←  |     |     | →   |     |     |      |      |        |

# Handoff



## Intra-cell

Change frequencies to avoid interference

## Inter-cell – Intra-BSC

MS moves between cells within control of one BSC

## Inter-BSC – Intra-MSC

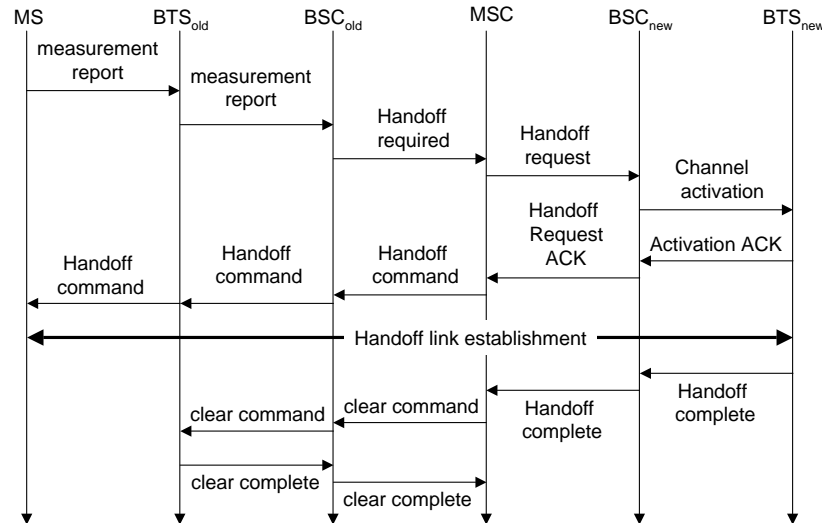
MS moves between cells controlled by different BSCs

MSC controls handover

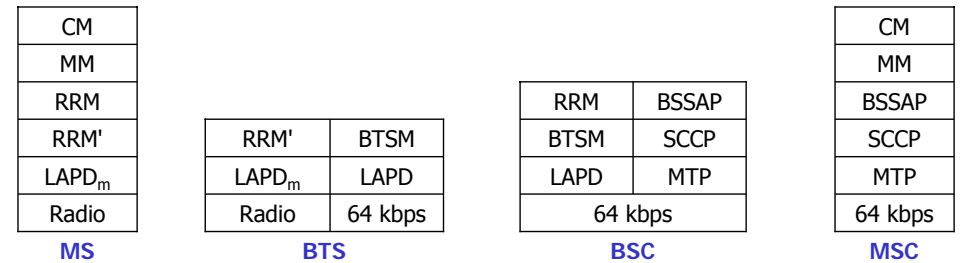
## Inter MSC

MS moves between cells controlled by different MSCs

# Handoff Procedure

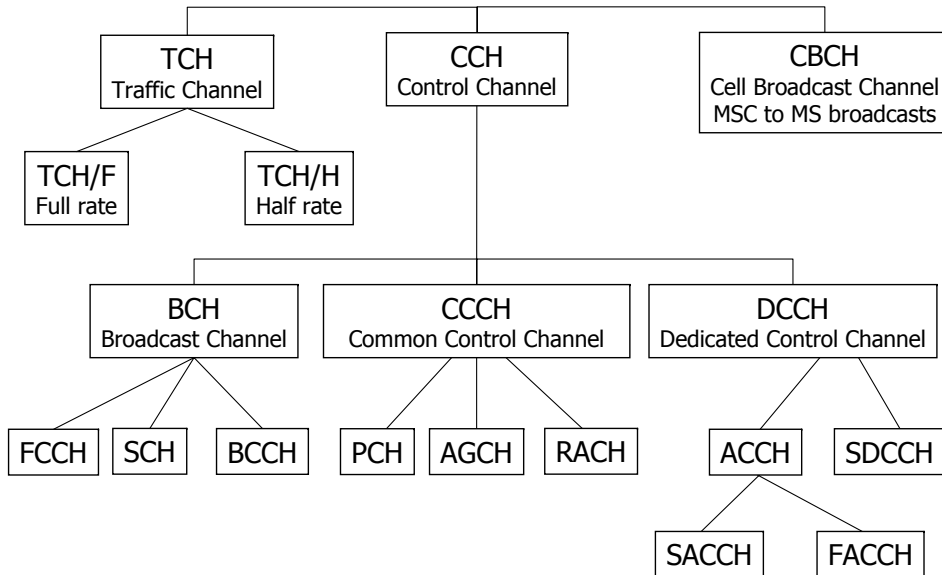


# GSM Protocol Stack



|       |   |
|-------|---|
| CM    | Connection Management   |
| MM    | Mobility Management   |
| RRM   | Radio Resource Management<br>Separate protocol instances at MS/BTS layer and MS/BSC layer |
| LAPD  | Link Access Protocol D — ISDN layer 2 protocol (Q.920/921)                                |
| BTSM  | Base Transceiver Station Management   |
| BSSAP | BSS Application Part  |
| SCCP  | Signaling Connection Control Part (SCCP) — MSC/BSS management                             |
| MTP   | Message Transfer Part — standard PSTN signaling and management                            |

## GSM Logical Channel Structure



## GSM Control Channels

### BCH — Broadcast Channel

Frequency Correction Channel (FCCH)

Synchronization Channel (SCH) — frame numbers and cell ID

Broadcast Control Channel (BCCH) — broadcast services and cell ID

### Common Control Channel (CCCH)

Paging Channel (PCH)

Access Grant Channel (AGCH) — BTS assigns control channel to MS

Random Access Channel (RACH) — MS requests to BTS

### DCCH (Dedicated Control Channel)

SDCCH (Stand-alone Dedicated Control Channel)

Service requests, authentication, traffic channel assignment

Call establishment and mobility management

F/SACCH (Fast / Slow Associated Control Channel)

Preemptive / background messages for maintenance and handoff

## Direct Sequence Spread Spectrum (DSSS)

### Transmit data bit as chip sequence

Chip

Shortest binary pulse on transmission channel

n-chip sequence is symbol for one data bit

### Multiplies transmission rate

User generates data at m bits per second

Transmit n-chip sequence for every user bit

Example

1-sequence for data 1 = 10110100

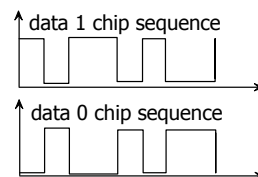
0-sequence for data 0 = 01001011

Chip rate =  $n \text{ bps} \times m \text{ chips per bit} = n \times m \text{ chips per second (cps)}$

### Receiver easily distinguishes 1-sequence from 0-sequence

Bit error requires  $> n / 2$  chip errors

Works well in noisy environment



## CDMA

### Code Division Multiple Access

Commercial system developed by Qualcomm

Operates on AMPS frequencies

### Non-AMPS channelization

25 MHz radio band per direction

Divide band into 1.25 MHz RF channels

25 MHz per cluster / 1.25 MHz per channel = 20 channels per cluster

### DSSS digital transmission

Transmit 1.2288 Mcps in 1.25 MHz radio channel

Voice and control modulation — QPSK

### Code division

Users transmit simultaneously using independent chip sequences

Orthogonal (Walsh) Codes / Pseudorandom noise (PN) codes

Receiver separates channels by decoding chip sequences

### Standards

IS-95 — now called CDMAone

## Orthogonal CDMA Codes

**m-dimensional vector space with inner product**

$$\mathbf{U} \cdot \mathbf{V} = \frac{1}{m} \sum_{i=1}^m U_i \times V_i$$

**m orthonormal basis vectors**

$$S_i, i = 1, \dots, m$$

$$\mathbf{T} = \sum_{i=1}^m t_i \times S_i, \text{ with coefficient } t_i \text{ for any vector } \mathbf{T}$$

$$S_i \cdot S_j = m \times \delta_{ij} = \begin{cases} 0, & i \neq j \\ m, & i = j \end{cases}$$

$$t_i = S_i \cdot \mathbf{T} = S_i \cdot \frac{1}{m} \sum_{j=1}^m t_j \times S_j = \frac{1}{m} \sum_{j=1}^m t_j \times (S_i \cdot S_j) = \frac{1}{m} \sum_{j=1}^m t_j \times m \delta_{ij} = t_i$$

**Code scheme**

Basis vector  $S_i$  is code assigned to station  $i$   
 Station  $i$  transmits  $t_i \times S_i$  with coefficient  $t_i = \begin{cases} -1, & \text{data 0} \\ 0, & \text{no transmission} \\ +1, & \text{data 1} \end{cases}$   
 Total transmission from all stations

$$\mathbf{T} = \sum_{i=1}^m t_i \times S_i$$

## Example — 4-Chip CDMA

**Code vectors for m = 4 stations**

$$S_1 = \begin{bmatrix} -1 \\ -1 \\ -1 \\ -1 \end{bmatrix} \quad S_2 = \begin{bmatrix} -1 \\ +1 \\ +1 \\ -1 \end{bmatrix} \quad S_3 = \begin{bmatrix} -1 \\ -1 \\ +1 \\ +1 \end{bmatrix} \quad S_4 = \begin{bmatrix} -1 \\ +1 \\ -1 \\ +1 \end{bmatrix}$$

**4-bit transmission levels (chips)**

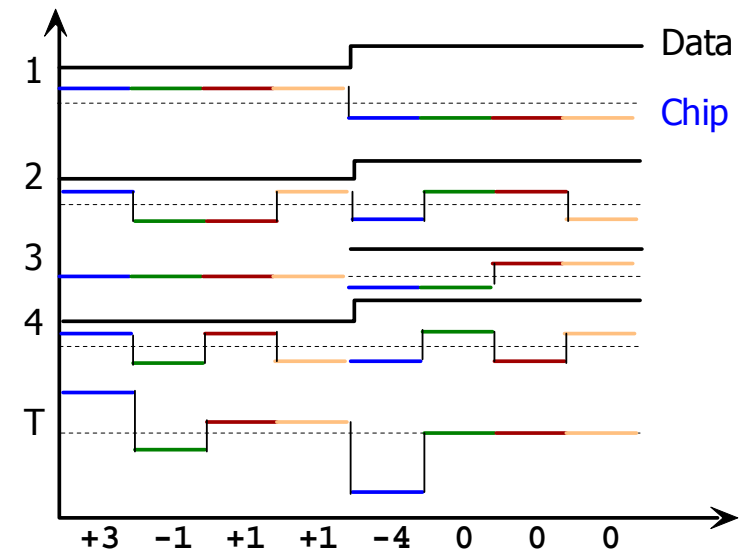
|           | Binary 1 |    |    |    | Binary 0 |    |    |    |
|-----------|----------|----|----|----|----------|----|----|----|
| Station 1 | -1       | -1 | -1 | -1 | +1       | +1 | +1 | +1 |
| Station 2 | -1       | +1 | +1 | -1 | +1       | -1 | -1 | +1 |
| Station 3 | -1       | -1 | +1 | +1 | +1       | +1 | -1 | -1 |
| Station 4 | -1       | +1 | -1 | +1 | +1       | -1 | +1 | -1 |

**Radio signal amplitudes added together**

## Example — 2-bit Transmission

|                    |        |             |             |
|--------------------|--------|-------------|-------------|
| Station 1          | Data   | 0           | 1           |
|                    | Signal | +1 +1 +1 +1 | -1 -1 -1 -1 |
| Station 2          | Data   | 0           | 1           |
|                    | Signal | +1 -1 -1 +1 | -1 +1 +1 -1 |
| Station 3          | Data   | no data     | 1           |
|                    | Signal | 0 0 0 0     | -1 -1 +1 +1 |
| Station 4          | Data   | 0           | 1           |
|                    | Signal | +1 -1 +1 -1 | -1 +1 -1 +1 |
| Total Transmission | Signal | +3 -1 +1 +1 | -4 0 0 0    |

## Example — 2-bit Transmission



## Example — Decoding

### Inner Product

$$\mathbf{U} \cdot \mathbf{V} = \frac{1}{4} \sum_{i=1}^4 U_i V_i \quad t_j = \mathbf{T} \cdot \mathbf{S}_j$$

|   |  |
|---|--|
| <b>First bit</b><br>$\mathbf{T} = (+3, -1, +1, +1)$ | $t_1 = \frac{1}{4}(3, -1, +1, +1) \cdot (-1, -1, -1, -1) = \frac{1}{4}[-3 + 1 - 1 - 1] = -1 \Rightarrow 0$<br>$t_2 = \frac{1}{4}(3, -1, +1, +1) \cdot (-1, +1, +1, -1) = \frac{1}{4}[-3 - 1 + 1 - 1] = -1 \Rightarrow 0$<br>$t_3 = \frac{1}{4}(3, -1, +1, +1) \cdot (-1, -1, +1, +1) = \frac{1}{4}[-3 + 1 + 1 + 1] = 0 \Rightarrow \text{no data}$<br>$t_4 = \frac{1}{4}(3, -1, +1, +1) \cdot (-1, +1, -1, +1) = \frac{1}{4}[-3 - 1 - 1 + 1] = -1 \Rightarrow 0$ |
| <b>Second bit</b><br>$\mathbf{T} = (-4, 0, 0, 0)$   | $t_1 = \frac{1}{4}(-4, 0, 0, 0) \cdot (-1, -1, -1, -1) = \frac{1}{4}[4] = +1 \Rightarrow 1$<br>$t_2 = \frac{1}{4}(-4, 0, 0, 0) \cdot (-1, +1, +1, -1) = \frac{1}{4}[4] = +1 \Rightarrow 1$<br>$t_3 = \frac{1}{4}(-4, 0, 0, 0) \cdot (-1, -1, +1, +1) = \frac{1}{4}[4] = +1 \Rightarrow 1$<br>$t_4 = \frac{1}{4}(-4, 0, 0, 0) \cdot (-1, +1, -1, +1) = \frac{1}{4}[4] = +1 \Rightarrow 1$   |

## Orthogonal Walsh Codes

### Walsh 0

$$W_0 = \begin{bmatrix} 1 \end{bmatrix} \quad W_0' = \begin{bmatrix} -1 \end{bmatrix}$$

### Walsh 1

$$W_1 = \begin{bmatrix} W_1 & W_1 \\ W_1 & W_1' \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

### Walsh 2

$$W_2 = \begin{bmatrix} W_2 & W_2 \\ W_2 & W_2' \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} = \begin{bmatrix} S_1 \\ S_4 \\ S_3 \\ S_2 \end{bmatrix}$$

### Walsh 3

$$W_3 = \begin{bmatrix} W_4 & W_4 \\ W_4 & W_4' \end{bmatrix}$$

### Walsh N

$$W_N = \begin{bmatrix} W_{N-1} & W_{N-1} \\ W_{N-1} & W_{N-1}' \end{bmatrix}$$

Walsh N is  $2^N \times 2^N$  matrix

## Pseudo-Noise (PN) Coding

### Pseudorandom Bernoulli sequence of 1 or -1

Equivalent to sequence of  $m$  coin tosses

Nearly equal number of 1 and -1 in each code

By central limit theorem

$$P_{-1} = P(-1) = \frac{1}{2} + \delta \quad P_{+1} = P(+1) = \frac{1}{2} - \delta \quad |\delta| < \frac{1}{\sqrt{m}}$$

### Codes are "nearly orthogonal"

For codes A and B with chip patterns  $C_i^{(A)}$  and  $C_i^{(B)}$

$$A = B \Rightarrow \frac{1}{m} \sum_{i=1}^m C_i^{(A)} \times C_i^{(B)} = \frac{1}{m} \sum_{i=1}^m [\pm 1]^2 = 1$$

$$A \neq B \Rightarrow \frac{1}{m} \sum_{i=1}^m C_i^{(A)} \times C_i^{(B)}$$

$$= \frac{1}{m} \sum_{i=1}^m [P_{+1} \times P_{+1} - P_{+1} \times P_{-1} - P_{-1} \times P_{+1} + P_{-1} \times P_{-1}] = 4\delta^2 < \frac{4}{m}$$

## Channel Coding

### Forward channels

64 orthogonal Walsh codes to 64 users

Theoretically perfect separation between users

All signals in same cell scrambled using PN sequence

Reduces interference between same Walsh code in neighboring cells

Short PN sequence uses cell ID as seed

Paging and traffic scrambled with long PN sequence before Walsh

### Reverse channels

Orthogonal codes not applicable in uplink

Orthogonality requires time synchronization

MSs transmit asynchronously

Long PN sequence

Stream is scrambled using short PN sequence

Carries cell ID

## Power Control

### Near/far problem

Signal from MS close to BS stronger than same signal from far MS

### Solution — dynamic control of MS signal power

#### Open loop power control at MS

MS senses strength of pilot signal and adjusts power

Strong signal

MS close to BS

Power lowered

#### Closed loop power control at MS

Power control information sent to MS from BS

Requests transition up or down in power

#### Open loop power control at BS

BS decreases power gradually (to avoid interference in other cells)

Raises power when MS reports high frame error rate (FER)

## North American IS-95 CDMA

### 25 MHz AMPS frequency band

1.25 MHz per FDM band  $\Rightarrow$  20 FDM bands

### In every 1.25 MHz FDM band

64 users transmit in same 1.25 MHz band (on same carrier frequency)

Each station has unique 64-bit chip sequence

### Digital channel

Allocate 19.2 kbps / user for voice, data, control

19.2 kbps/channel  $\times$  64 channels = 1.2288 Mbps

### All cells use all frequencies and all codes (reuse = 1)

Transmissions from neighboring cells are not time-synchronized

Unsynchronized codes are close to orthogonal

### Users

$$\frac{64 \text{ users}}{\text{radio channel}} \times \frac{20 \text{ channels}}{\text{cell}} \times \frac{7 \text{ cells}}{\text{cluster}} = 8,960 \frac{\text{users}}{\text{cluster}}$$

## Reuse Pattern in GSM and CDMA

### GSM

Transmit 8 time slots on 1 FDM channel

Channels on different FDM channels do not interfere

Channels in different time slots do not interfere

Each cell uses 1/7 to 1/3 of all FDM channels to avoid interference

Minimum distance between cells on same frequency = 2

### CDMA

Transmit 64 different codes on 1 FDM channel

Channels on different FDM channels do not interfere

Channels using different codes do not interfere

All codes and FDM channels used in all cells

Most codes do not interfere when not synchronized

User at cell boundary assigned a non-interfering code

Multipath signals are not synchronized

## GSM and CDMA Multiplexing

|                            | GSM                                   | CDMA                                |
|----------------------------|---------------------------------------|-------------------------------------|
| <b>Total Bandwidth</b>     | 25 MHz                                | 25 MHz                              |
| <b>FDM Bandwidth</b>       | 200 kHz                               | 1.25 MHz                            |
| <b>Radio channels</b>      | 25 MHz / 200 kHz = 125                | 25 MHz / 1.25 MHz = 20              |
| <b>User bit rate</b>       | 22.8 kbps                             | 19.2 kbps                           |
| <b>Users per channel</b>   | 8                                     | 64                                  |
| <b>Bit rate in channel</b> | 8 $\times$ 22.8 kbps = 182.4 kbps     | 64 $\times$ 19.2 kbps = 1.2288 Mbps |
| <b>Total Bit Rate</b>      | 182.4 kbps $\times$ 124 = 22.6 Mbps   | 1.2288 Mbps $\times$ 20 = 24.6 Mbps |
| <b>Reuse</b>               | 2, 3, 7                               | 1                                   |
| <b>Channels per cell</b>   | 124 / 7 $\approx$ 17                  | 20                                  |
| <b>Users per cell</b>      | (124 / 7) $\times$ 8 $\approx$ 141    | 20 $\times$ 64 = 1280               |
| <b>Users per cluster</b>   | (124 / 7) $\times$ 8 $\times$ 7 = 992 | 20 $\times$ 64 $\times$ 7 = 8960    |

### CDMA principal advantage — reuse

GSM with reuse = 1  $\Rightarrow$  992 users / cell  $\times$  7 cells / cluster = 6944 users per cluster

## CDMA Codes Compared to TDMA

### CMDA

- Each station transmits a 64-bit code
- All stations transmit continuously at the same
- Transmissions are separated by orthonormality of codes

### CMDA codes

- $2^{64}$  different 64-bit sequences
- 64 orthogonal 64-bit sequences
- Orthogonal transformation on orthogonal code is an orthogonal code

$$S_i^{(j)} = i\text{'th chip in code basis vector } j$$

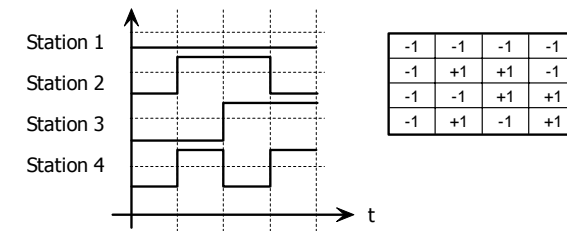
$$S_i^{(j)} = \sum_{k=1}^{64} T_{ik} S_k^{(j)} = i\text{'th chip in new code basis vector } j$$

$$\text{Orthogonal matrix } T_{ik} = T_{ki}^{-1}$$

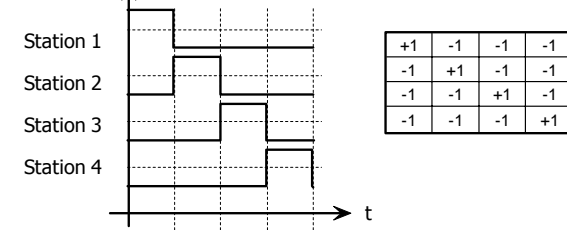
- Pick  $S_i^{(j)} = \delta_{ij}$  System looks like TDMA
- Station  $i$  only transmits on chip  $i$
- Station  $i$  transmits 1 bit per chip sequence

## CDMA Codes and TDMA "Codes"

4 Chip Walsh Codes



4 Chip TDM "Codes"



## Noise Immunity in GSM and CDMA

### GSM transmits

- 8 user samples transmitted in time required to make 1 sample
- Each 5 ms sample transmitted in  $5 \times (24/26) \times (1/8) = 0.58$  ms
- 8 voice streams of 22.8 kbps = 182.4 kbps in 200 kHz
- Shannon: Required SNR =  $2^{182.4/200} - 1 = 0.88$

### CDMA transmits

- 1 user voice sample transmitted in time to make 1 voice sample
- No time multiplexing
- Every user transmits a different set of symbols
- 64 symbols transmitted at one time with multilevel modulation
- 64 voice streams of 19.2 kbps = 1.2288 Mbps in 1.25 MHz
- Shannon: Required SNR =  $2^{1.2288/1.25} - 1 = 0.98$
- Better noise immunity because of noise averaging

## Noise Averaging in CDMA

### Total transmitted data from 64 users

$$\mathbf{T} = \sum_{i=1}^{64} t_i S_i$$

### Total received signal

$$\mathbf{T} = \sum_{i=1}^{64} t_i S_i + \text{noise} = \sum_{i=1}^{64} t_i S_i + N_i 1_i$$

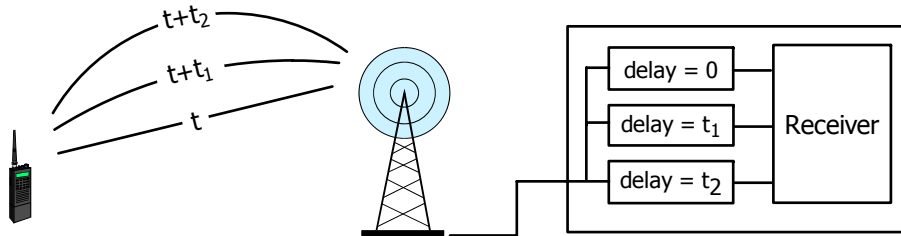
### Calculated coefficient for user i is

$$\begin{aligned} \text{Calculated } t_j &= (\mathbf{T} + \text{Noise}) \cdot S_{(j)} = \left( \sum_{i=1}^{64} t_i S_{(i)} + N \right) \cdot S_{(j)} \\ &= \sum_{k=1}^{64} \left( \sum_{i=1}^{64} t_i S_{(i)}^k + N^k \right) \cdot S_{(j)}^k, N^k \text{ is noise amplitude on chip } k \\ &= \sum_{i=1}^{64} t_i \sum_{k=1}^{64} S_{(i)}^k \cdot S_{(j)}^k + \sum_{k=1}^{64} N^k \times S_{(j)}^k \\ &= \sum_{i=1}^{64} t_i \delta_{ij} + \sum_{k=1}^{64} N^k \times 1 \text{ (if } S_{(j)}^k = 1) - N^k \times 1 \text{ (if } S_{(j)}^k = -1) \\ &= t_j + \langle \text{Noise} \rangle_{\text{chip} = +1} - \langle \text{Noise} \rangle_{\text{chip} = -1} \end{aligned}$$

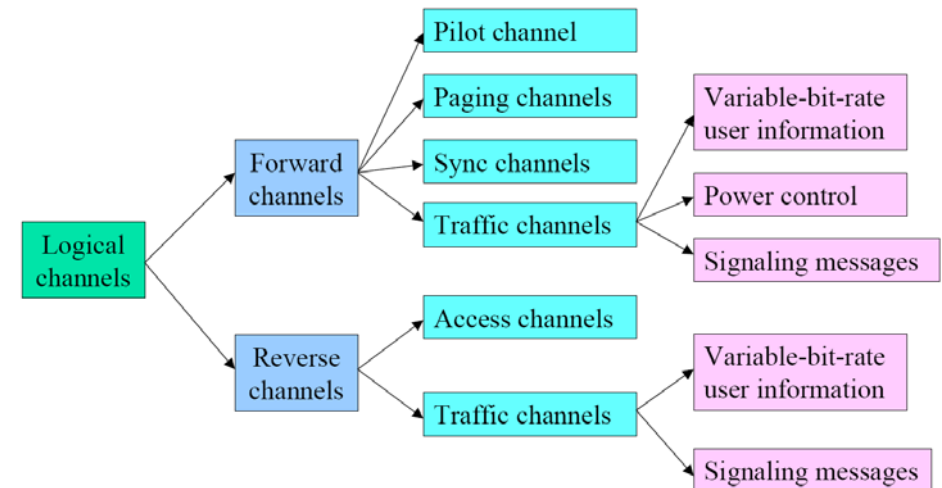
## Rake Receiver

### Overcomes multipath interference

Captures delayed signals in multipath reception  
Adds contributions from all paths



## Logical Channels



## Forward Logical Channels

### Pilot channel

Transmitted in all frames  
Phase and timing reference for MS  
Provides signal strength to MS for channel acquisition  
Reused in every cell with local short PN code offset  
1 pilot frame per 64 channel system

### Sync channel

Timing, system and, network IDs to MS  
Can be received by MS after locking onto pilot signal  
8 synch frames per 64 channel system

### Forward traffic channels

User data and signaling data  
Two modes

Blank and burst — signaling data instead of voice  
Dim and burst — multiplexes signaling data with voice data  
55 traffic frames per 64 channel system

## Reverse Logical Channels

### Access channel

Random access channel used by MS for messages to BS  
Contention access

Choose access channel at random

Collision  $\Rightarrow$  lost data  $\rightarrow$  no ACK  $\rightarrow$  retry after random wait

Paired with up to 32 paging channels

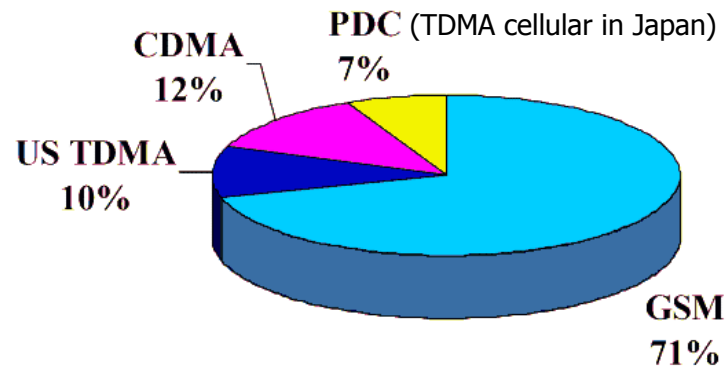
MS responds to paging message on corresponding access channel

### Reverse traffic channel

User data (primary and secondary) and signaling  
Signaling information multiplexed with user data  
Variable data rates

## Distribution of 2G Systems

Cellular telephones in use — July 2001



Source: EMC World Cellular / GSM Association