Consider a cellular communications system with hexagonal cells each containing a base station and a number of mobile units.

**Assumptions**
- Each cell is divided into 3 sectors and perfect isolation is possible between sectors.
- All users employ different spreading codes.
- Perfect power control (all fast fading (Rayleigh) and slow fading (due to shadowing)). The power received at the mobile (or base) from different users is the same.
- Negligible thermal noise.
- Voice Activity results in reduced interference.
- Every cell uses the same frequency band. Interference from other cells is included.
- Bandwidth $W$, Data Rate $R_b$.

Consider user $A$. The output of the receiver matched to user $A$'s code sequence is

$$X(T) = \sqrt{E}b_0 + \eta$$

where $\eta$ accounts for the interference from all other users and $b_0$ denotes the data bit transmitted $\in \{+1, -1\}$.

The variance of $\eta$ is given by

$$\sigma^2 = \frac{K-1}{3N}E$$

assuming random delays for the interfering users and random phases.

If on the other hand we looked at the worst possible phase and delay for each of the interfering users the variance would be

$$\sigma^2 = \frac{K-1}{N}E$$

The ratio of the magnitude of the output due to the desired signal and the square root of the variance of the interference determines the signal-to-noise ratio. Assuming the worst case phases and delays

$$SNR = \frac{\sqrt{E}}{\sigma} = \sqrt{\frac{N}{K-1}}$$

If we were not using any coding then the error probability (under a Gaussian approximation) is given by

$$P_{e,b} = Q(SNR)$$

For other coding schemes the relation between the error probability and signal-to-noise ratio...
is more complicated.

However, if an acceptable signal-to-noise ratio (at the output of the demodulator) is determined from the coding scheme employed then it is possible to calculate the capacity (calls per cell) of a Direct Sequence CDMA. The voice activity factor (usually taken to be 1/2) reduces the amount of interference by turning down the power when slower data rates are possible (because of voice inactivity). The interference from other cells is taken to be 66% of the interference from within the cell of the user. Thus the variance of the interference can be modified to taken account the voice activity and the interference from other cells as follows

\[ \sigma^2 = \frac{(K-1)ED}{NF} \]

where

- \( D = \) Voice Activity Factor, \( \ldots 1/2 \)
- \( F = \) Frequency Reuse Factor, \( \ldots 0,6 \)

The modified signal-to-noise ratio is

\[ SNR = \sqrt{\frac{N}{K-1}F/D} = \sqrt{\frac{FW}{(K-1)RF_D}} \]

Thus the number of calls per sector \( K_s \) for an output signal-to-noise ratio of \( SNR \) is

\[ K_s = 1 + \frac{W}{R_b} \left( \frac{SNR}{G} \right)^2 \frac{1}{DF} \]

\[ \approx \frac{W}{R_b} \left( \frac{SNR}{G} \right)^2 \frac{1}{DF} \]

The number of calls per cell is then \( K_c \) is given by

\[ K_c \approx \frac{W}{R_b} \left( \frac{SNR}{G} \right)^2 \frac{1}{DF} \]

Example

- \( W = 1.25 \) MHz
- \( R_b = 9600 \) bits/second
- \( (SNR)^2 = 6dB = 4 \)
- \( G = 3 \) sectors/cell

Users/cell for DS-CDMA = 117.2 users per 1.25 MHz per cell. FDMA has a capacity of 6 channels or users per cell per 1.25 MHz.

TDMA has a capacity of 17.6 channels or users per cell per 1.25 MHz.

Caveat: These number are quite optimistic (especially for DS-CDMA). Many engineers believe that the capacity for CDMA is more realistically on the order of 40-50 calls/cell. Imperfect power control is one key factor that reduces the actual capacity coupled with the fast fading which can not be compensated for by power control.

### Potential Advantages of CDMA for Digital Cellular

- Voice Activity
- No Equalizer (to eliminate intersymbol interference)
- One Radio per Basestation (Front end)
- Soft Handoff
- No Guard Time (Required by TDMA)
- Less Fading
- Frequency Management Eliminated
- Frequency Reuse=1

Disadvantages:
- Power Control
- Transition from Narrowband system to wideband system
IS-95 Standard for Cellular Transmission

- Speech Encoding
- Network Issues
- Reverse Link
  - Error Control Coding
  - Modulation
  - Spreading
- Forward Link
  - Error Control Coding
  - Modulation
  - Spreading

Speech Encoder

- Voice is encoded by means of a variable rate speech encoder. The possible data rates are 8600 bps, 4000 bps, 2000 bps, 800 bps. When operating at a lower rate users turn down the power on forward link and gate the power off on the reverse link (to maintain a fixed $E_b/N_0$) and thus cause less interference for other users. After a small amount of overhead (CRC and tail bits for the convolutional code) the rates are 9600, 4800, 2400 and 1200 bits/second.
- The system bandwidth of 1.23MHz using pseudo-random spreading-codes. Multiple users occupy the whole bandwidth simultaneously (but with different phases of a very long spreading code)
- The near-far problem typical of DS-CDMA is solved with power control.

Network Issues

Logically there are a number of different “channels” (using different orthogonal Walsh functions on the forward link and different phases of a spreading code on the reverse link) besides those used for sending voice traffic. These include the following:

Forward Traffic Channels

Forward CDMA Channels
1.23MHz channel transmitted by base station

Addressed by Orthogonal Walsh Code
Forward Traffic Channels

- **Pilot Channel**: Transmitted on the forward channel and used to identify the base stations within range of the mobile. The mobile keeps a list of the nearest base stations. This channel is also used to provide phase synchronization for the mobile and channel gain estimates.

- **Paging Channel**: Transmitted on the forward channel and used in setting up a call to or from a mobile. Transmits data at rates of 2400, 4800, 9600 bps. Used to assign a Walsh code (Hadamard sequence) for the forward traffic channel. It is also used to identify other neighboring base stations for the purpose of handoff processing.

Forward Traffic Channels (cont.)

- **Sync Channel**: Transmitted on the forward channel and used to bring the mobile unit into synchronization (timing) with the base. Contains timing information with regard to the long code that is used to identify users.

- **Power Control Subchannel**: Transmitted on the forward channel. The voice traffic is replaced with power control bits once every 1.25ms or power control group used by the mobile to increase or decrease the transmitted power. One power control bit is transmitted with duration of 2 modulation symbols or 104,166µs. The power level for transmission of the power control bit is the same as would be transmitted by a full rate (high power) traffic channel even when the traffic channel is transmitting at a lower power level.

Reverse Traffic Channels

Reverse CDMA Channels
1.23MHz channel received by base station

Access Ch. 1 Access Ch. n Traffic Ch. 1 Traffic Ch. n

Addressed by Long Code

Reverse Traffic Channels

- **Access Channel**: Transmitted on the reverse channel and used to alert the base to mobile initiated calls and to respond to pages (on the paging channel). It is used in a random access mode (Aloha) by mobiles.

- **Traffic Channel**: Transmitted on the forward and reverse links. Used to transmit voice or data traffic. Can operate at rates of 1200bps, 2400bps, 4800bps, and 9600bps.
**Block Diagram of Transmitter**

- **Long Code Generator**
- **Orthogonal Modulator**
- **Rate 1/3 Convolutional Encoder**
- **Interleaver**
- **Randomizer**
- **Add 8 bit Encoder Tail**
- **Add 12/8 bit CRC for 9600 and 4800 bps rates**

---

**Reverse Link Traffic Channel Parameter**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>9600</th>
<th>4800</th>
<th>2400</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate bps</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN Chip Rate</td>
<td>1.2288</td>
<td>1.2288</td>
<td>1.2288</td>
<td>1.2288</td>
</tr>
<tr>
<td>Code Rate</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>100</td>
<td>50</td>
<td>25</td>
<td>12.5 percent</td>
</tr>
<tr>
<td>Code Symbol Rate</td>
<td>28.8</td>
<td>28.8</td>
<td>28.8</td>
<td>28.8 sps</td>
</tr>
<tr>
<td>Modulation</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Walsh Chip Rate</td>
<td>307.2</td>
<td>307.2</td>
<td>307.2</td>
<td>307.2 kcps</td>
</tr>
<tr>
<td>Mod Symbol Duration</td>
<td>208.33</td>
<td>208.33</td>
<td>208.33</td>
<td>208.33 µs</td>
</tr>
<tr>
<td>PN Chips/Code Symbol</td>
<td>42.67</td>
<td>42.67</td>
<td>42.67</td>
<td>42.67</td>
</tr>
<tr>
<td>PN Chips/Mod Symbol</td>
<td>256</td>
<td>256</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>PN Chips/Walsh Chip</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

---

**Constraint Length 9, Rate 1/3 Convolutional Encoder**

---

**Figure 151**: 12 bit CRC Encoder. Switches are up for first 172 bits and down for last 12 bits.

**Figure 152**: 8 bit CRC Encoder. Switches are up for first 172 bits and down for last 8 bits.
Interleaver

The convolutional encoder output is interleaved using different size interleavers. For the high rate data stream the interleaver is a 32 by 18 interleaver. Symbols are written into the interleaver memory column-wise and read out row-wise. Thus if the sequence of symbols at the input to the interleaver is \( c_1, c_2, c_3, \ldots \), the sequence of symbols at the output of the interleaver is \( c_1 c_3 c_5 \ldots \).

For the 9600 bps channel the rows are read out consecutively. For the 4800 bps channel the rows are read out in the following order:

\[
1 \quad 2 \quad 4 \quad 5 \quad 7 \quad 6 \quad 8 \quad 9 \quad 11 \quad 10 \quad 12 \quad 13 \quad 15 \quad 14 \quad 1 \quad 7 \quad 19 \quad 18 \quad 20 \quad 21 \quad 23 \quad 22 \quad 24 \quad 25 \quad 27 \quad 26 \quad 28 \quad 29 \quad 30 \quad 32
\]

For the Access channel the rows are read out in the following order:

\[
1 \quad 7 \quad 9 \quad 5 \quad 5 \quad 21 \quad 13 \quad 29 \quad 3 \quad 19 \quad 11 \quad 27 \quad 23 \quad 15 \quad 31 \quad 2 \quad 18 \quad 10 \quad 26 \quad 6 \quad 22 \quad 14 \quad 30 \quad 4 \quad 20 \quad 12 \quad 28 \quad 8 \quad 24 \quad 16 \quad 32
\]

Interleaver

For the 4800 bps data rate each symbol is repeated twice in the interleaver memory. However, one of the two rows is not actually transmitted. Which row is selected is determined from the data burst randomizer. Similarly, for the 2400 bps data rate each symbol is repeated four times but only one of every set of four rows is actually transmitted. For the 1200 bps data rate each symbol is repeated 8 times but only one of every 8 rows is selected by the data burst randomizer.
while the low order 32 bits are set to a permutation of the mobiles electronic serial number (ESN)
Spreading

Each Walsh chip $w_i$ is spread by a factor of 4 using the long code. Then each of the chips is used for both the inphase and quadrature phase channels. Each of these channels is scrambled according to the base stations short codes. This scrambling is equivalent to a phase shifter as shown below. Let $u$ be the output of the long code spreading operation. Then if we express the inphase and quadrature phase signals as complex variables the output after scrambling by the short codes $\{s_i, s_q\}$, $s_i, s_q \in \{\pm 1\}$ is

$$v = u s_i + j u s_q$$
$$v = u(s_i + j s_q)$$

After receiving the signal there is some unknown phase shift (due to delay) in the received signal. The received signal is

$$r = ve^{j\theta}$$

To remove this scrambling function we must multiply by $s_i - j s_q$.

$$z = r(s_i - j s_q)$$

$$= ve^{j\theta}(s_i - j s_q)$$
$$= u(s_i^2 + s_q^2)e^{j\theta}.$$  
$$= 2ue^{j\theta}.$$  

Since $s_i^2 + s_q^2 = 2$ we have removed all aspect of the scrambling function from the desired user.

Short Codes

The two short codes are generated by m-sequences with feedback connections

$$i_n = i_n 15 + i_n 10 + i_n 8 + i_n 7 + i_n 6 + i_n 2$$
$$q_n = q_n 15 + q_n 12 + q_n 11 + q_n 10 + q_n 9 + q_n 5 + q_n 4 + q_n 3$$

When the shift register is in the state with 14 zeros and 1 one a zero is inserted to make the length of the sequence $2^{15}$ (instead of $2^{15} - 1$)

Each base station uses the same shift register for the short code but the phase of the sequence is shifted by multiples of 64 chips between one base station and another base station.
Reason for Offset QPSK on Reverse Link (Mobile-to-Base)

On the link from the mobile to base battery power is a crucial issue. The use of high efficiency amplifiers warrants the use of amplifiers operating in the nonlinear range. If the signal is not of constant envelope or nearly constant envelope there would be distortion to the signal when amplified. For a nonconstant envelope signal the nonlinearity can regenerate some sidebands that have been filtered out by the baseband filters. If standard QPSK had been used the signal would be much less constant envelope (the signal going through the origin would have significant envelope variations especially after being filtered). This would cause significant distortion of the signal and the regeneration of the sidebands.

On the link from the base to the mobile battery life is not an issue and only one amplifier needs to be built (for all of the signals). Thus some care can go into designing a linear amplifier.

Phase Shifting Network

The above phase shifter does the following computation.

\[ (x_m + jy_m)(z_r - jz_i) = x_m z_r + y_m z_i + j(y_m z_r - x_m z_i) \]

where \( r \) \( \theta \) = \( z_r - jz_i \).

Frame Structure

<table>
<thead>
<tr>
<th>Information Rate per Frame</th>
<th>172</th>
<th>80</th>
<th>40</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>6400 bits/frame</td>
<td>184</td>
<td>88</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>3200 bits/frame</td>
<td>192</td>
<td>96</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>1280 bits/frame</td>
<td>192</td>
<td>96</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>640 bits/frame</td>
<td>256</td>
<td>128</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>320 bits/frame</td>
<td>256</td>
<td>128</td>
<td>64</td>
<td>32</td>
</tr>
</tbody>
</table>

Block Diagram
**Block Diagram of Mobile Transmitter Access Channel**

**Reverse Link Access Channel Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Data Rate (bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN Chip Rate</td>
<td>1.2288 Mcps</td>
</tr>
<tr>
<td>Code Rate</td>
<td>1/3 Mcps</td>
</tr>
<tr>
<td>Code Symbol Repetition</td>
<td>2</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>100 percent</td>
</tr>
<tr>
<td>Code Symbol Rate</td>
<td>28.8 sps</td>
</tr>
<tr>
<td>Modulation</td>
<td>6 code sym/mod symbol</td>
</tr>
<tr>
<td>Modulation Symbol Rate</td>
<td>4800 symbols/sec</td>
</tr>
<tr>
<td>Walsh Chip Rate</td>
<td>307.2 kcps</td>
</tr>
<tr>
<td>Mod Symbol Duration</td>
<td>208.33 µs</td>
</tr>
<tr>
<td>PN Chips/Code Symbol</td>
<td>42.67</td>
</tr>
<tr>
<td>PN Chips/Mod Symbol</td>
<td>256</td>
</tr>
<tr>
<td>PN Chips/Walsh Chip</td>
<td>1</td>
</tr>
</tbody>
</table>

**Encoder for Reverse Link of IS-95**

<table>
<thead>
<tr>
<th>Bits per Frame</th>
<th>172</th>
<th>80</th>
<th>40</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>8.6kbps</td>
<td>4.0kbps</td>
<td>2.0kbps</td>
<td>0.8kbps</td>
</tr>
<tr>
<td></td>
<td>Add 128 bit CRC for 9600 and 4800bps rates</td>
<td>Add 8 bit Encoder Tail</td>
<td>Rate 1/3 Convolutional Encoder</td>
<td>Rate 1/3 Convolutional Encoder</td>
</tr>
</tbody>
</table>

**Spreading for Reverse Link of IS-95**

- I Channel Sequence: 24576 chips
- Q Channel Sequence: 1.2288Mcps
- 6144 Walsh chips per 20ms: 576 bits/20ms
- 64-ary Orthogonal Modulator: 6 to 64
- Data Burst Randomizer: 307.2kbps
- 64-ary Orthogonal Modulator: 6 to 64
- Long Code Generator: 1.2288Mcbps
- Long Code Mask
Notes

1. For a 9600 bps frame the data burst randomizer does nothing.
2. For a 4800 bps frame the data burst randomizer removes half of the power control bit groups. The ones removed depend on the state of the long code generator in the previous speech frame.
3. For a 2400 bps frame the data burst randomizer removes three quarters of the power control bit groups.
4. For a 1200 bps frame the data burst randomizer removes seven eights of the power control bit groups.
5. The set of power control groups transmitted by a 1200 bps frame is a subset of that transmitted by a 2400bps frame which is a subset of that transmitted by a 4800bps frame.

Reverse Channel Modulation

- Baseband Filter
- Delay $T_c/2$
- Baseband Filter
- $\cos(2\pi ft)$
- $\sin(2\pi ft)$
Filter Characteristics for Baseband Filter

Filter Requirements: \( \delta_1 = 1.5\,\text{dB}, \delta_2 = 40\,\text{dB}, f_p = 590\,\text{kHz}, f_s = 740\,\text{kHz} \)

Reason for Offset QPSK on Reverse Link (Mobile-to-Base).

On the link from the mobile to base battery power is a crucial issue. The use of high efficiency amplifiers warrants the use of amplifiers operating in the nonlinear range. If the signal is not of constant envelope or nearly constant envelope there would be distortion to the signal when amplified. For a nonconstant envelope signal the nonlinearity can regenerate some sidebands that have been filtered out by the baseband filters. If standard QPSK had been used the signal would be much less constant envelope (the signal going through the origin would have significant envelope variations especially after being filtered). This would cause significant distortion of the signal and the regeneration of the sidebands.

On the link from the base to the mobile battery life is not an issue and only one amplifier needs to be built (for all of the signals). Thus some care can go into designing a linear amplifier.

Reason for Augmenting the Short Code

The short code is base station specific. In synchronizing the system knowing the starting point of the short code determines the starting point of the modulation symbols since there is exactly an integer number of modulation symbols per short code period. If there were not an integer number then the short code synchronization would not be sufficient for modulation symbol synchronization.

Power Control

- Reverse Link:
  - Open Loop Analog: 85 dB range, few microsecond response for sudden improvement in channel, but slow power build up when channel is poor so that closed loop control can occur
  - Closed Loop: 1 dB every ms, or so, 24 dB change allowed (800 Hz. rate and 1.25 ms power control groups)
- Forward Link:
  - Approximately 0.5 dB or 12% every 15-20 ms 6 dB dynamic range
**System Timing**

The long code and the short code are in the state with 41 or 14 zeros and a single one on Jan 6, 1980 at 00:00:00 Universal Coordinated Time (UTC). The clock rate is 1.2288 MHz. The long code has period $2^{32} - 1$ while the short code has period $2^{15}$. The period of the combination is $(2^{32} - 1)(2^{15}) = 14411518807823104$ clock ticks.

**Notes**

1. The base station transmissions are all referenced to a system wide time scale using Global Position System time scale which is synchronous with Universal Coordinated Time (UTC). GPS and UTC differ by the number of leap seconds since January 6, 1980.
2. Alignment of the long code and short code will occur again in 37 centuries.
3. The mobile attempts to synchronize to System Time based on information received from base station transmissions.

**Transmitter for Pilot, Paging and Synch Channels**

The pilot short code spreading for different base stations are identical (except in the timing or sequence phase). They differ by a multiple of 64 PN chips. Thus a mobile using a single matched filter can determine the signal strength due to pilots signals from different base stations. This information is used to decide when to handoff to another base station.
Transmitter for Forward Link Traffic Channel

System Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>890-915 MHz</td>
</tr>
<tr>
<td>Mobile Transmit</td>
<td>935-960 MHz</td>
</tr>
<tr>
<td>Speech Coder Rate</td>
<td>13 kbps</td>
</tr>
<tr>
<td>Information Bits/Speech Frame</td>
<td>182 Class I, 78 Class II, 260 Total</td>
</tr>
<tr>
<td>Speech Frame Duration</td>
<td>20 ms</td>
</tr>
<tr>
<td>Channel Encoding</td>
<td>50 Class I bits protected with 3 parity bits, All Class I bits and previous parity bits protected with rate 1/2 convolutional code.</td>
</tr>
<tr>
<td>Overall code rate</td>
<td>260/456 = 0.570 information bits/channel bit</td>
</tr>
</tbody>
</table>

GSM and IS-54/136

European Mobile Communication System
Global System for Mobile Communications (GSM)

This is a second generation cellular phone developed in Europe to create a system for all Europe (replacing the analog systems in many countries).
Figure 154: Transmitter Block Diagram for GSM

Figure 155: Error Control Coding for GSM

Reordering

\[
d(0) \ d(1) \ d(2) \ \ldots \ d(50) \ p(0) \ p(1) \ p(2) \ d(51) \ d(52) \ \ldots \ d(181) \\
\downarrow \\
\ d(0) \ d(2) \ d(4) \ \ldots \ d(180) \ p(0) \ p(1) \ p(2) \ d(181) \ d(179) \ \ldots \ d(1) 
\]

Figure 156: GSM Convolutional Encoder
Figure 157: GSM Frame Structure

Interleaving for GSM

Figure 158: Interleaving for GSM
This is a second generation cellular phone developed for the US market and standardized in 1990. It is very similar to PHS in Japan.
System Characteristics

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>824-849MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Transmit</td>
<td>869-893 MHz</td>
</tr>
<tr>
<td>Speech Coder Rate</td>
<td>7.95kbps</td>
</tr>
<tr>
<td>Information Bits/Speech Frame</td>
<td>77 Class I</td>
</tr>
<tr>
<td></td>
<td>82 Class II</td>
</tr>
<tr>
<td></td>
<td>159 Total</td>
</tr>
<tr>
<td>Speech Frame Duration</td>
<td>20 ms</td>
</tr>
<tr>
<td>Channel Encoding</td>
<td>12 Class I bits protected with 7 parity bits</td>
</tr>
<tr>
<td></td>
<td>All Class I bits and previous parity bits protected with rate 1/2 convolutional code.</td>
</tr>
<tr>
<td>Overall code rate</td>
<td>159/260=0.612 information bits/channel bit</td>
</tr>
</tbody>
</table>

System Characteristics (cont.)

<table>
<thead>
<tr>
<th>Multiple Access</th>
<th>TDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Duration</td>
<td>40ms</td>
</tr>
<tr>
<td>Slots/Frame</td>
<td>6</td>
</tr>
<tr>
<td>Slot Duration</td>
<td>6.66ms</td>
</tr>
<tr>
<td>Coded Symbols/Slot</td>
<td>260</td>
</tr>
<tr>
<td>Instantaneous Rate</td>
<td>48.6 kbps</td>
</tr>
<tr>
<td>Modulation Rate</td>
<td>24.3 ksps</td>
</tr>
<tr>
<td>Modulation</td>
<td>$\pi/4$ DQPSK, Raised Cosine Filtered with $\alpha = 0.35$</td>
</tr>
<tr>
<td>Symbol alphabet</td>
<td>Quaternary (differentially encoded)</td>
</tr>
<tr>
<td>Carrier Spacing</td>
<td>30kHz</td>
</tr>
</tbody>
</table>

Figure 162: Frame Structure of IS-54

Each user is assigned two of the six slots. Full rate users are assigned two slots which are either slots 1 and 4 or 2 and 5 or 3 and 6. Half rate users are assigned one channel. Thus every 30kHz channel is used by three full rate users and thus the capacity is three times that of AMPS.

Figure 163: Slot Format for IS-54

G= Guard Time   RSVD= Reserved
R= Ramp Time    SACCH=Slow Associated Control Channel
Data= User Information or FAACH CDVCC=Coded Digital Verification Color Code
**Control Channels**
The Slow and Fast Associated Control Channel is used for signalling bits such as for handoff, power control and timing. The Fast Associated Control Channel is transmitted in a blank and burst mode, that is, the traffic information for a slot is replace by signalling information for that slot.

**Color Code**
The CDVCC is used to distinguish signals from different cells. There are 255 possible values for CDVCC which is coded with an (12,8) shortened Hamming code for error protection.

**Power Control**
Mobile must be capable of changing the power transmitted in 4dB steps from -2dBW to -34dBW on command from the Base Station.

**Time Control**
Mobile must be capable of changing the time of transmission of a slot in steps of duration 1/2 a symbol.

**Figure 164: Block Diagram of Encoding for IS-54**

**Figure 165: Block Diagram of Encoding for IS-54**

**Figure 166: Encoding for IS-54**
The 2-slot interleaver works as follows. The even numbered bits are written into one interleaver in the even numbered locations while the odd numbered bits are written into a second interleaver. These are written in column-wise filing up the first column, then the second column and so on. (The even numbered bits are denoted by x and the odd numbered bits are denoted by y below). The transmitted bits for a given slot are the contents of one of the interleavers read out row-wise.

Thus the order of bits transmitted would be the following.

Bit 0 from current speech frame.
Bit 26 from current speech frame.
Bit 52 from current speech frame.
Bit 78 from current speech frame.
Bit 104 from current speech frame.
Bit 130 from current speech frame.
Bit 156 from current speech frame.
Bit 182 from current speech frame.
Bit 208 from current speech frame.
Bit 234 from current speech frame.
Bit 1 from previous speech frame.
Bit 27 from previous speech frame.
Bit 53 from previous speech frame.
Synchronization Sequences are shown below with the autocorrelation functions shown below.

Figure 168: Autocorrelation function of synchronization sequences

Demodulation/Decoding

Error in transmission can cause the CRC for the 12 most perceptually significant bits to fail. When a slot is used as a FACCH the CRC will likely fail also.

The decoder has six states.

State 0: CRC checks, and the received data is used by the speech decoder.

State 1 CRC Fails: The 12 bits from the previous frame are used for the 12 most perceptually significant bits.

State 2 Two consecutive CRC Fails: The 12 bits from the previous correct frame are used for the 12 most perceptually significant bits.

State 3-6 Three consecutive CRC Fails: The 12 bits from the previous correct frame are used for the 12 most perceptually significant bits except the speech frame energy is attenuated by 4dB in state 3, 8dB in state 4, 12 dB in state 5 and the speech frame is muted in state 6.

In states 2-5 a correct CRC brings the decoder state to 0. In state 6 two consecutive correct CRC's bring the encoder to state 0.