4 CDMA Technique

Objectives:

After this chapter the student will:

- be able to understand concept of DS-CDMA and RAKE receiver.
- be able to understand soft handover and the need for power control.

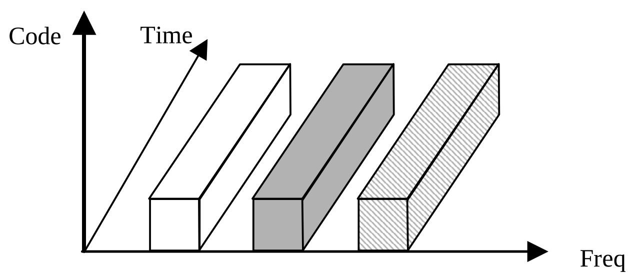
4.1 Introduction

Code-division multiple access, CDMA is a spread-spectrum communication system in which multiple users have access to the same frequency band. This chapter will provide an introduction to CDMA and its concepts.

4.2 Access Methods FDMA, TDMA, CDMA, FDD vs. TDD

Frequency Division Multiple Access (FDMA)

In FDMA schemes, the entire available frequency is divided into bands, each of which is assigned to a station. FDMA is characterised by continuous access to the terminal/mobile in a given frequency band. No co-ordination or synchronisation is required among stations. Each station can use its own band without interference. However, FDMA is the cause of waste especially when the load is momentarily uneven. When a station is idle, its share of the bandwidth cannot be used by other stations. FDMA is also not flexible; adding a new station requires equipment modifications.



FDMA

Advantages

This technique has the advantage of simplicity, and it relies on the use of proven equipment.

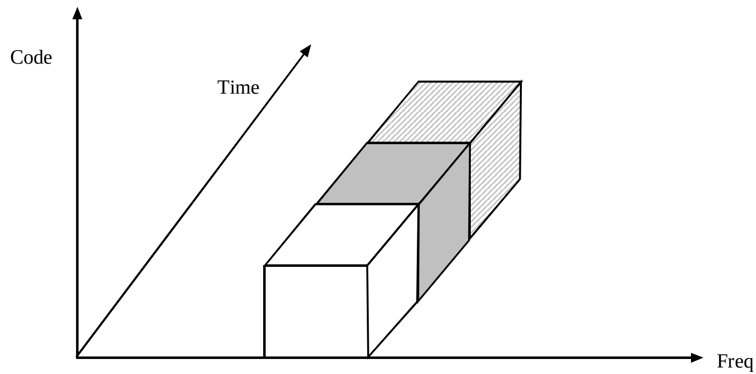
Disadvantages

Lack of flexibility in case of reconfiguration such as accommodation of capacity variation.

Time Division Multiple Access (TDMA)

In TDMA schemes, the time is divided into time slots. Each time slot is pre-assigned to a station. During the assigned slot, each station is allowed to transmit freely, and the entire system resources are devoted to the station. The slot assignments are periodic, and each period is called a cycle or a frame. A station could be assigned to one or more time slots during a cycle. The stations must be synchronised so that each station knows exactly when to transmit.

The major disadvantage of TDMA is the requirement that each station must have a fixed allocation of channel time whether or not it has data to transmit. In most applications transmission requirements are bursty. For these applications, a fixed allocation of channel time to each station is wasteful of resources.



Picture TDMA

<u>Advantages</u>
At each instant, a single station occupies all of the channel bandwidth. High transmission throughput for a large number of stations. There is no need to control the transmitting power of the stations. Digital processing leads to operational simplicity. All stations transmit and receive on the same frequency, this simplifies tuning.

<u>Disadvantages</u>
Synchronisation is needed. The need to dimension the station for transmission at high throughput. Needs costly equipment, however, the cost can be compensated by better channel utilisation and hence better throughput.

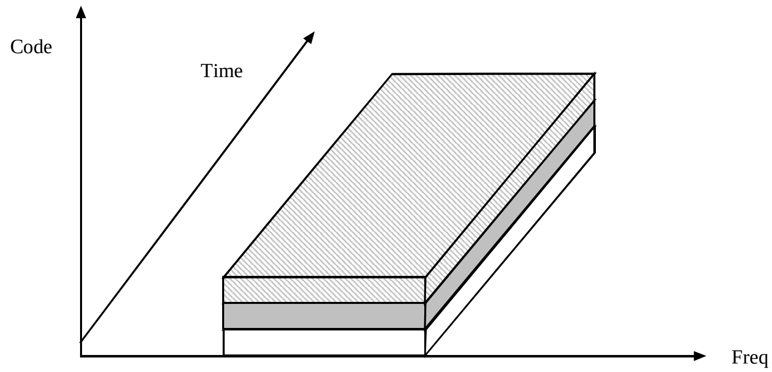
Code Division Multiple Access (CDMA)

Neither FDMA nor TDMA allow any time overlap of the stations transmissions. A conflict-free protocol that allows overlap transmission, both in frequency division and time division techniques, is Code Division Multiple Access (CDMA).

The conflict-free property of CDMA is achieved by using quasi-orthogonal signals in conjunction with matching filters at the receiving stations. Using multiple orthogonal signals (information that does not interfere with each other) increases the bandwidth required for transmission. CDMA allows the coexistence of several systems in the same frequency bands using different signals. Transmission of the code requires a much greater radio-frequency bandwidth. This is the reason for calling it Spread Spectrum transmission. In CDMA each station is assigned a particular code sequence which is modulated on the carrier with the digital data modulated on top of that.

There are two common forms: 1) frequency-hopped in which the frequency is periodically changing according to some known pattern, and 2) phase-coded in which the carrier is phased-modulated by the digital data sequence and the code sequence.

Even when several stations employ the same code, the effect of interference is minimised by the capture effect, which is the ability of the receiver to lock onto one packet while all other overlapping packets appear as noise.

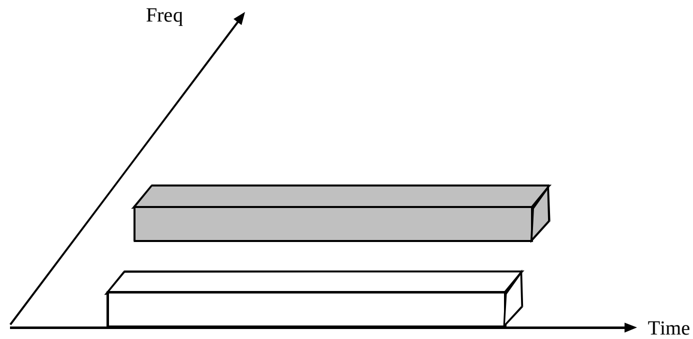


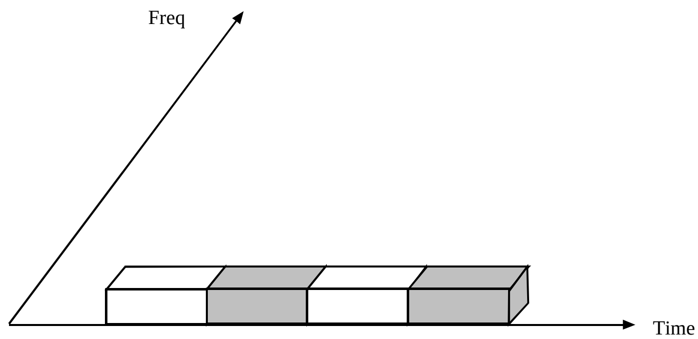
Picture CDMA

<u>Advantages</u>
It is simple to operate since it does not require any transmission synchronisation between the mobile stations. It offers protection properties against interference from other systems.

<u>Disadvantages</u>
The main disadvantage is the low throughput.

FDD vs. TDD





In the frequency division duplex mode, FDD, the connection between a mobile and a basestation will be on separate frequencies in the uplink and downlink. This means that the mobile will transmit on one frequency and then receive on another frequency. The FDD mode those not imply any specific access method.

In time division duplex, TDD, the connections up and downlink will be on only one frequency. The TDD mode those not imply any specific access method.

4.3 Introduction to Spreading and Modulation

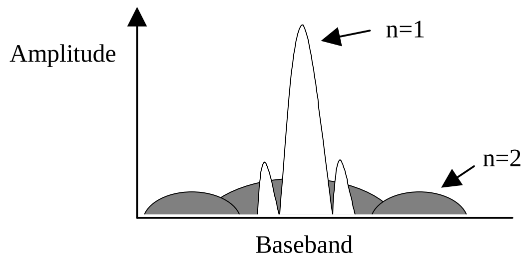
Spread spectrum systems generally fall into one of two categories: frequency hopping (FH) or direct sequence (DS). In both cases synchronisation of transmitter and receiver is required. Both forms can be regarded as using a pseudo-random carrier, but they create the carrier in different ways.

Frequency hopping is typically accomplished by rapid switching frequency in a pseudo-random pattern.

In DS-CDMA spread spectrum refers to power spreading over a given transmission bandwidth.

This is accomplished by spreading the base-band binary data by means of a high speed pseudo-noise (PN) code called the chip rate. The composite data are then modulated and transmitted over the air.

Spectrum spreading can be accomplished by increasing the frequency of the time signal. If we have a waveform with an amplitude **V** and frequency **f** (where f = 1/T and **T** is the bit duration) and then increase the frequency by a factor *n*, T is now reduced by *n*.



Power spectrum for n = 1 and n = 2

The total energy delivered is given by the total area under the curve. This means that the total energy remains the same after spreading and if the spreading bandwidth is high the amplitude of the signal will be reduced. This is called process gain.

Process gain is defined as Gp = 10 log (transmission bandwidth / bit rate). If for example the transmission bandwidth is 2,5 MHz and the bitrate is 1 MHz the process gain would be 3,98 dB. If we increase the bandwidth to 5 MHz the process gain would be 6,99 dB. This would provide us with an additional margin of 3 dB margin to help us suppress interference.

If you are not familiar with decibel, dB, 3 dB means two times. 3 dB + 3 dB + 3 dB means 2 * 2 * 2 equal to 8 times and so on.

The margin described above is reduced when more and more users enters the system since there will be a processing loss for every new user (interferer) that enters the system. For **k** users this loss can be described as Process loss = 10 log (**k**).

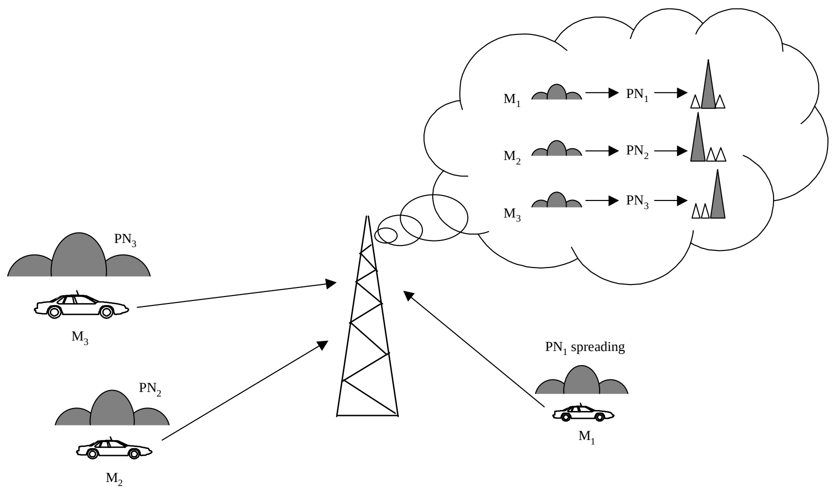
The overall system gain is the described by CDMA gain = Process gain – Process loss due to k users. The formula would become

CDMA gain = 10 log (bandwidth / k * bit rate)

where the bandwidth is as described a function of the chiprate.

Important to notice is that energy is independent of the frequency and that the amplitude of the signal will be reduced after spreading. If the bandwidth is enough the amplitude will be close to the noise level, that is, the Gaussian "white noise" that we always have around us.

In CDMA multiple users uses the same frequency. This is done with the help of an m-bit PN generator which provides 2^{m-1} different codes. From these codes each user will have its own code.



UL DS-CDMA

<u>Orthogonal Codes</u>

A pair of codes is said to be orthogonal if the cross-correlation is zero. This means that for two m-bit codes: x1, x2, …, xm and y1, y2, …, ym the sum of all m from 1 to m shall be 0. For example, the cross-correlation between two 4-bits codes:

X = 0 0 1 1
Y = 0 1 1 0

Will be

-1 -1 1 1
-1 1 1 -1
____
1 - 1 + 1 – 1 = 0

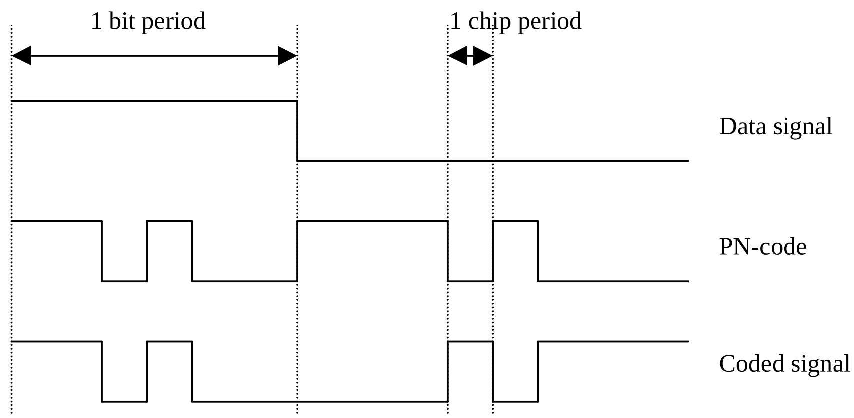
Direct sequence is multiplication of a more conventional communication waveform by a pseudonoise (PN) ±1 binary sequence in the transmitter.

In reality spreading takes place prior to any modulation, entirely in the binary domain, and the transmitted signals are carefully bandlimited.

A second multiplication by a replica of the same ±1 sequence in the receiver recovers the original signal.

The noise and interference, being uncorrelated with the PN sequence, become noise-like and increase in bandwidth when they reach the detector. The signal-to-noise ratio, SNR, can be enhanced by narrowband filtering that rejects most of the interference power.

In DS-CDMA the data signal (user information) is multiplied by a PN-code. The PN code is a sequence of chips (we denote the user information bits and the spreading bits chips) valued 0 and 1. The number of chips within one code is called the period. There exist several classes PN-codes, M-sequences, Gold-codes and Kasami-codes for example. In the most simple case a complete PN-code is multiplied with a single data bit and the signal is now multiplied by a factor N, the processing gain.



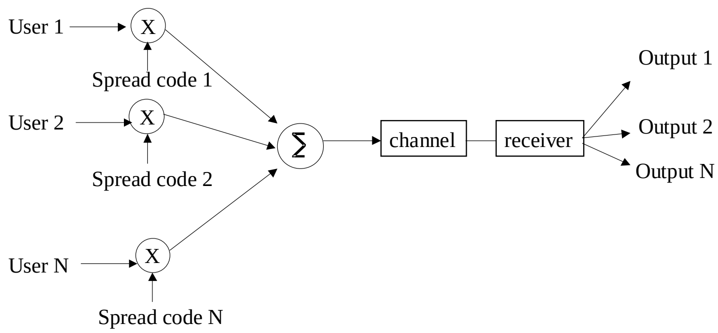
Chips and bits

In the receiver the signal is multiplied by the same PN-code which removes the PN-code and gives us the data signal.

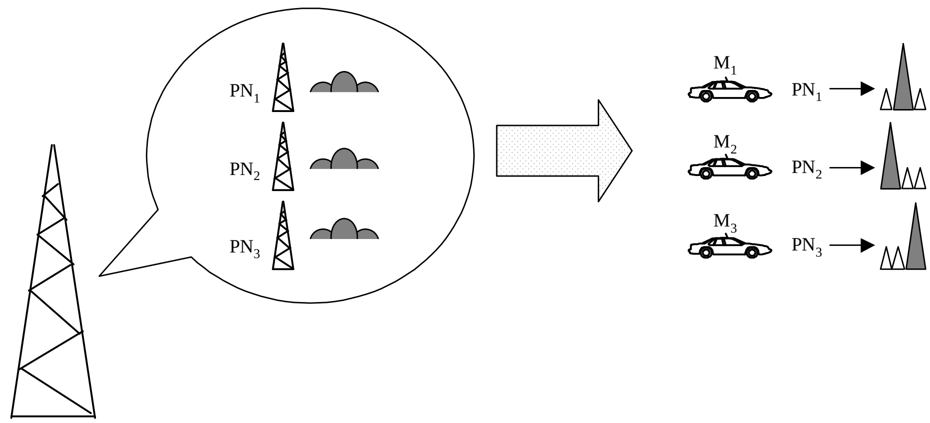
The pseudorandom (PN) sequence generator produces a binary value sequence that is used to spread and de-spread the transmitted signal (data information) at the modulator/demodulator. The basic system design parameters *are transmitted power* and *channel bandwidth*.

To overcome the problem of interference we increase (spread) the bandwidth of the data signal that will lead to a bandwidth expansion factor, *process gain*, g = W/R where W is the spread code bandwidth (chiprate) and R is the data bandwidth (bitrate).

When we use different PN-sequences for each user, we can use the same transmission bandwidth for more than one user.

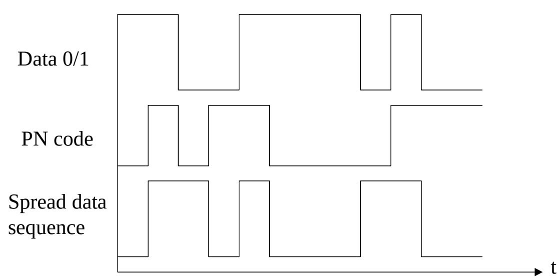


Different PN-sequences



Different PN-sequences for each user

If the spreading is done by a different PN-sequence for many users then it is called direct sequence code division multiple access, DS-CDMA



DS-CDMA principle

If the random code pattern is nearly Gaussian distributed, then we get a similar signal as thermal noise (white noise). Thus we can simplify and say that, the interference of the other users is noise.

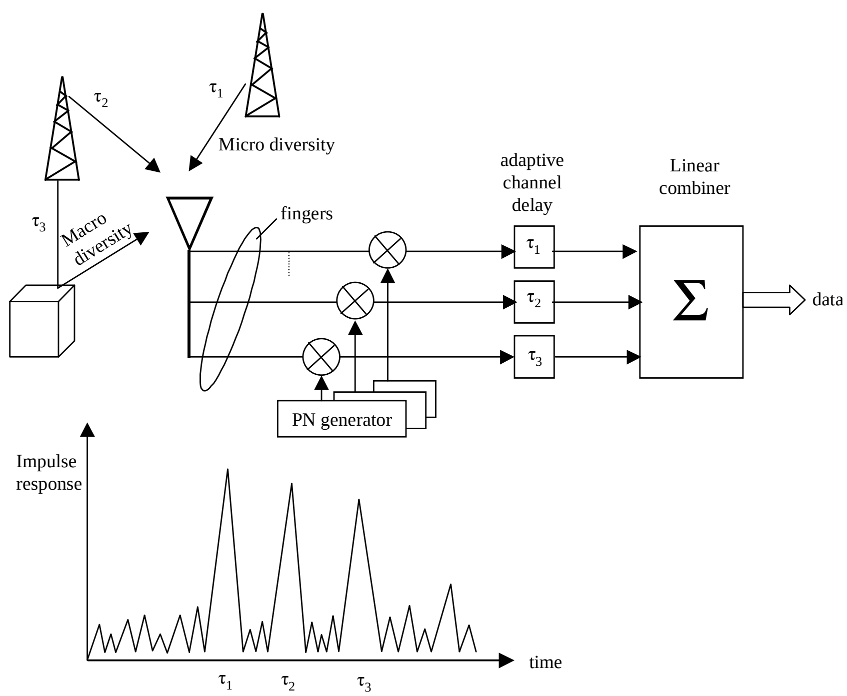
DS-CDMA uses orthogonal code for spreading and channelisation. PN codes are used to detect each multi-path signal and to pick up the signals from the desired base station.

By using much higher rate spreading codes, DS-CDMA spreads the original information over wide bandwidth and makes use of frequency diversity to combat frequency selective deep fading. Filtering is essential in DS-CDMA to reduce the required bandwidth and FIR digital filters are usually used for sharp response.

RAKE receiver

Users in a CDMA cellular environment simultaneously share the same radio frequency band and can be separated at the receiver end with the knowledge of their unique code using a "RAKE"-receiver.

CDMA is less prone to deep multipath fading caused by transmissions arriving at the receiver that have followed different propagation paths. In fact, one approach in common use with CDMA systems, the RAKE-receiver, takes advantage of multipath, normally a major source of interference and signal degradation in other systems. In a RAKE-receiver, the signals of several correlation receivers belonging to the strongest multipath components are combined to provide an enhanced signal with better quality.



RAKE receiver

To be able to despread the wanted signal in the receiver both the right coding and the right timing must be done. An optimum receiver contains several detection channels with different code delays, which are adjusted to mach the major components of the impulse response.

In the RAKE receiver the contribution from several multipath components are combined. It is necessary to measure continuously the impulse response of the propagation channel in order to set the delay and phase on the different rake branches. The output from the channels can then be added giving diversity combining.

The timing accuracy to obtain full processing gain is approximately one chip time, i.e. the inverse of the channel bandwidth. An optimum receiver contains several detection channels with different code delays, which are adjusted to match the major components of the impulse response. The fingers in the rake collects together the contributions of the total signal energy from several multipath components. The impulse response is measured continuously in order to set the delay and phase of the different rake fingers. Thus the output from the channels can be added coherently giving diversity combining.

Why Spread Spectrum?

Techniques known since 1940s and used in military communications systems since 1950s

“Spread” the radio signal over a wide frequency range by modulating it with a code word unique to the radio.

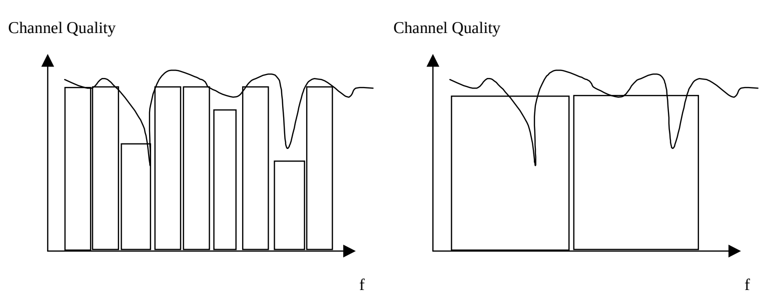
Receiver’s correlator distinguishes sender’s signal from other signals by examining the wide spectrum band with a time synchronised duplicate of the spreading code word.

The sent signal is recovered by a despreading process at the Receiver.

Spread spectrum waveform is more resistant to multipath effects and more tolerant of interference.

Spread spectrum systems are power rather than bandwidth limited

With a narrow bandwidth a user channel might receive severe fading dips while with a wider band the interference will have an averaging effect in such a way that all user will share the problem.



Interference averaging

Code Properties

The codes should have good Auto Correlation (Time Relation) and Cross Correlation (suppress other users) properties.

Short Codes:
Code sequence length = bit (bit = one bit user data)
Code sequence repeated for each new data bit
+ Orthogonal codes if perfect synchronisation
+ Good synchronisation properties
- Code planning needed since limited number of good short codes.

Long Codes:
Code sequence length >> bit
+ No code planning needed since low probability that users might have same code
- Non orthogonal codes
- Bad synchronisation properties since long repetition cycle.

4.4 Soft and Hard Handover

Handover

In general, handover is considered as the change of physical channels allocated to a call while maintaining this call. In a soft handover the mobile belong to two base stations during the time he moves between the cells (make before brake). While in a hard handover the mobile station will instructed to move from one channel to another and only be receiving from one base station at a time (break before make).

Soft handover

When in active mode, the mobile station continuously searches for new base stations on the current carrier frequency. During the search, the mobile station monitors the received signal level from neighbouring base stations, compares them to a set of thresholds, and reports them accordingly back to the base station. Based on this information the network orders the mobile station to add or remove base station links from its active set. The active set is defined as the set of base stations from which the same user information is sent simultaneously.

Softer handover

Softer handover is the special case of a soft handover between sectors/cells belonging to the same base station site.

Conceptually, a softer handover is initiated and executed in the same way as an ordinary soft handover. The main differences are on the implementation level within the network.

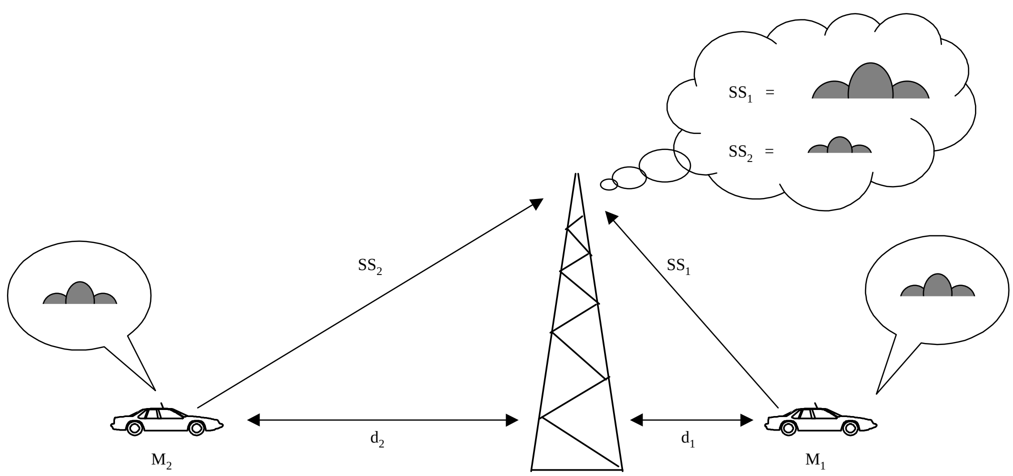
Intra-frequency handover is a handover between cells using the same (single) radio frequency whereas inter-frequency handover is a handover between cells using different radio frequencies.

The inter-frequency handover is always performed as a hard handover.

4.5 Power Control

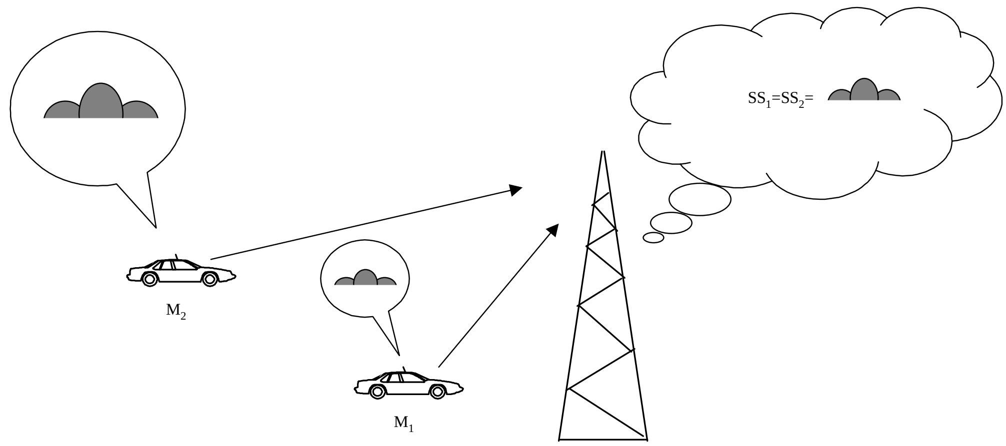
In an interference limited system (CDMA), many simultaneous connections share a common transmission channel. While in FDMA each connection has its one frequency and in TDMA each connection has one time slot, this will permit high isolation between the connections (orthogonality).

Since we have several users in the same frequency band the received signal strength will be different for different mobiles, resulting in a near-far interference problem. Near-far refers to the ratio of signal strength from a near mobile to a mobile far away. This problem will give lower performance and reduce capacity in the system.



Near-far

If the mobiles would transmit the same power the ratio of the received signal would be: RS1/RS2 = $(d2/d1)^{\lambda}$ where lambda is the path loss or propagation environment. If d1 is not equal to d2 then the received signal strength from mobile 1 might be much stronger than mobile 2 and the receiver would not be able to detect and recover mobile 2. This means that the transmitting power of each mobile has to be controlled so that the received power is constant irrespective of the distance.



controlled transmitting power

In an interference limited system we assign a specific code to each connection. This will help us to discriminate between the wanted signal C and interference I from all other users.

When the total interference level is increased (more users), there will be a point when the C/I becomes to low. This is called anti-jamming margin, AJ, which is the maximum value for I/C. This gives us an interference limited system for CDMA compared to FDMA and TDMA who are channel limited system.

To get an acceptable isolation between the connections we need a large bandwidth which will increase the AJ. The processing gain, Gp, is a related parameter, also related to the bandwidth. The Gp determines how much the receiver can suppress the interference.

It is then very important with power regulation so that all signals have the same level at the receiver input.

For high values of G p (>1000), information can be transmitted at power levels below ambient noise. This means low probability of intercept/detect" and narrowband jamming or interference.

Commercially available SS systems typically implement processing gains in the 10-100 range

To illustrate the problem and advantages with an interference limited system, the "International Cocktail Party" analogy can be used. Picture a large room with a number of people, in pairs, who would like to hold conversations.
The people in each pair only want to talk and listen to each other, and have no interest in what is being said in other pairs. In order for these

conversations to keep place, however, it is necessary to define the environment for each conversation.

If people speak in different languages, Gp is high and it is easier to distinguish individual speakers. Now if a band is playing we get a ”random noise” and the Gp will be lower, I/C increases, and it will be more difficult to extract the conversation from the background.

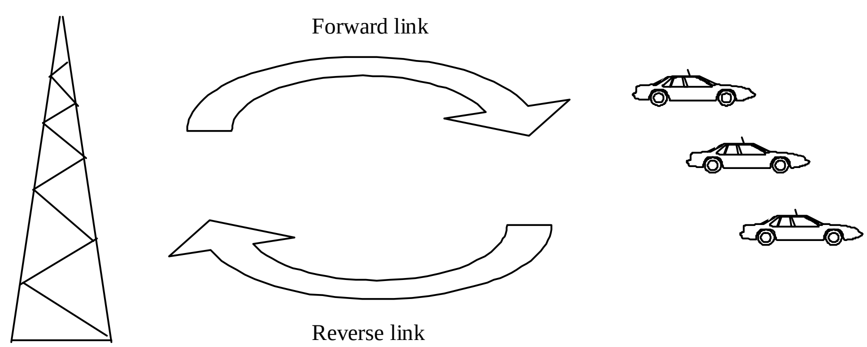
Now image that the Band starts playing even louder! Speakers try to talk more loudly, increasing the noise and if more and more people enters the room each conversation will be louder and louder to cope with the interferers.

The solution is to have the participants to agree to speak more softly when a new guest arrives. This could be done with the help of a host that require all guests to speak to him at the same relative level, no matter how far from they are from the host.

Power control to minimise the interference level at the base station receiver is only effective for terminals assigned to this base station. Interference from terminals in other cells is still a problem. To minimise this interference we need to use soft handover and careful selection of which base station shall be involved in macro diversity.

Closed loop power control –uplink

The uplink closed loop power control adjusts the mobile station transmit power in order to keep the received uplink Signal-to-Interference Ratio (SIR) at a given SIR target. The base station should estimate the received uplink power after RAKE combining of the connection to be power controlled. Simultaneously, the base station should estimate the total uplink received interference in the current frequency band and generate a SIR estimate. The base station then generates TPC (Transmit Power Control) commands.



Forward and reverse link

Upon the reception of a TPC command, the mobile station should adjust the transmit power of the uplink in the given direction with a step of ΔTPC dB. The step size ΔTPC is a parameter that may differ between different cells, in the region 0.25 – 1.5 dB.

In case of receiver diversity (e.g., space diversity) or softer handover at the base station, the TPC command should be generated after diversity combining.

In case of soft handover, the following procedure is considered:

- in the base stations a quality measurement is performed on the received signals; in case the quality measurement indicates a value below a given threshold, an increase command is sent to the mobile, otherwise a decrease command is transmitted; all the base stations in the active set send power control commands to the mobile

- the mobile compares the commands received from different base stations and increases its power only if all the commands indicate an increase value (this means that all the receivers are below the threshold)

- in case one command indicates a decrease step (that is, at least one receiver is operating in good conditions), the mobile reduces its power; in case more than one decrease commands are received by the mobile, the mobile station should adjust the power with the largest step in the "down" direction ordered by the TPC commands received from each base station in the active set.

- the quality threshold for the base stations in the active set should be adjusted by the outer loop power control (to be implemented in the network node were soft handover combining is performed).

Outer loop (SIR target adjustment) - uplink

The outer loop adjusts the SIR target used by the closed-loop power control. The SIR target is independently adjusted for each connection based on the estimated quality of the connection. In addition, the power offset between the uplink may be adjusted.

Open-loop power control - uplink

Open-loop power control is used to adjust the transmit power of the physical access channel. Before the transmission of a access burst, the mobile station should measure the received power of the downlink. From the power estimate and knowledge of the transmit power from the base station (broadcasted from the base station) the downlink path-loss including shadow fading can be found. From this path loss estimate and knowledge of the uplink interference level and the required received SIR, the transmit power of the physical access channel can be determined.
The uplink interference level as well as the required received SIR are broadcast from the base station.

Closed loop power control - downlink

The downlink closed loop power control adjusts the base station transmit power in order to keep the received downlink SIR at a given SIR target.

The mobile station should estimate the received downlink power after RAKE combining of the connection to be power controlled. Simultaneously, the mobile station should estimate the total downlink received interference in the current frequency band. The mobile station then generates TPC commands.

Upon the reception of a TPC command, the base station should adjust the transmit power in the given direction with a step of ΔTPC dB. The step size ΔTPC is a parameter that may differ between different cells, in the range 0.25 – 1.5dB.

In case of receiver diversity (e.g., space diversity) at the mobile station, the TPC command should be generated after diversity combining.