

# CDMA – Code Division Multiple Access

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**Abstract**—Code Division Multiple Access (CDMA) is probably the most interesting multiple access method provided by spread spectrum technology. CDMA refers to a multiple access method in which the individual terminals use spread-spectrum techniques and occupy the entire spectrum whenever they transmit.

This paper focuses on direct-sequence spread-spectrum principles (processing gain, spreading, de-spreading, modulation and codes) and more into CDMA cellular system fundamentals like multiple access interference (MAI), multipaths, RAKE receiver, power control and soft handover. Also the capacity of a CDMA system is discussed.

Also CDMA applications in cellular system standards such as IS-95, CDMA2000 and Wideband CDMA are briefly introduced.

**Index Terms**—CDMA, Code Division Multiple Access, spread-spectrum system, direct-sequence.

## I. INTRODUCTION

CDMA refers to a multiple access method in which the individual terminals use spread-spectrum techniques and occupy the entire spectrum whenever they transmit. This feature makes CDMA different from frequency division multiple access (FDMA) and from time division multiple access (TDMA). In FDMA each user is given a small portion of the total available spectrum, and in TDMA each user is allowed full use of the available spectrum, but only during certain periods in time.

Code Division Multiple Access is a modulation and multiple access scheme based on the spread-spectrum communication technology. It is well-established technology and applied to digital cellular radio and wireless communication systems in the early 1990s. Capacity concerns of major markets and efficient and economic wireless communication needs of the industries were the most significant drivers for the development of the CDMA cellular technology.

CDMA is a method in which users share time and frequency allocations, and are channelized by unique assigned codes. The signals of different users are separated at the receiver by using a correlator that captures signal energy only from the desired user or channel. Undesired signals contribute only to noise and interference. Figure 1 illustrates the principle of the CDMA technique.

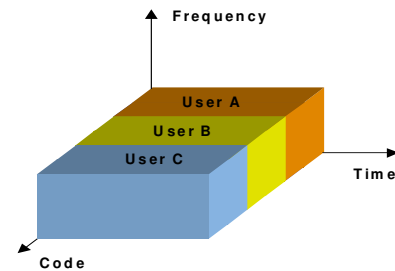


Figure 1. CDMA multiple access method

The development of the CDMA technique dates back to the early 1950s when different studies of the spread-spectrum technologies were started. The first era in CDMA history consisted of introducing basic ideas of the CDMA by Claude Shannon and Robert Pierce in 1949. In 1950 De-Rosa-Rogoff defined the direct-sequence spread-spectrum method, the processing gain equation, and a noise multiplexing idea. Price and Green filed the RAKE receiver patent in 1956. In 1961 Manuski defined the near-far problem crucial for CDMA systems. During the 1970s several military and navigation applications were developed. [1]

The second CDMA era introduced studies focusing on narrowband systems. In 1978 Cooper and Nettleton suggested a cellular spread-spectrum application. During the 1980s communication company Qualcomm investigated narrowband CDMA techniques for cellular applications, and the result was that in 1993 the CDMA IS-95 standard was developed [1]. Compared to third generation CDMA systems IS-95 can be considered a narrowband CDMA system with 1.2288 Mchip/s carrier chip rate. Third generation wideband CDMA systems, such as CDMA IS-2000 and European WCDMA use higher chip rates than CDMA IS-95.

## II. SPREAD-SPECTRUM TECHNOLOGY

Originally, the spread-spectrum technology has been developed for military and navigation purposes because it has some interesting characteristics that provide secure means of communication in hostile environments [2]. First of all, spread spectrum signals have LPI-properties (Low Probability of Interception), and cannot be easily detected by enemy communication equipment due to low power spectral density, even lower than background noise. Secondly, spread-spectrum signals have efficient AJ (Anti-Jamming) properties to combat intentional interference trying to sabotage

communication systems [3]. Nowadays, spread-spectrum technology has also proven to be feasible for commercial applications especially for mobile communication systems. It provides an efficient multiple access method for a number of independent users sharing a common communication channel without external synchronization methods. CDMA is probably the most interesting multiple access method provided by spread-spectrum technology.

The fundamental idea of spread-spectrum communication is to spread a certain information bandwidth,  $B_i$ , over a wider transmission bandwidth,  $B_t$ . The minimum of the transmission bandwidth has to be wider than the information bandwidth. The relative rate between user information and the pseudo-random code sequence can be on the order of tens or hundreds for commercial systems and on the order of thousands for military systems. Spread-spectrum communications cannot be said to be an efficient means of utilizing bandwidth because it needs a lot of bandwidth to be efficient. On the other hand, the wider transmitted bandwidth offers such a low power spectral density that it makes the transmitted signal look like background noise in front end of a receiver [3]. Besides LPI and AJ capabilities spread spectrum communication systems can offer further advantages such as multiple access, efficient privacy, and interference rejection.

There are two basic spread-spectrum techniques: direct sequencing (DS), frequency hopping (FH), and time hopping (TH). Also, a variety of hybrid techniques use different combinations of these basic techniques. With direct-sequence spreading, the original signal is multiplied by a known signal of much larger bandwidth. With frequency-hopped spreading, the center frequency of the transmitted signal is varied in a pseudorandom pattern.

#### A. Processing Gain

Combining a bit stream of information with an independent pseudo-random code sequence by simple multiplication carries out the spreading operation. One of the main parameters of a spread spectrum communication system is the processing gain,  $G_p$ . It is the ratio of the transmitted bandwidth,  $B_t$ , and information bandwidth,  $B_i$ , as presented in the following equation 1. [1]

$$G_p = \frac{B_t}{B_i} \quad (1)$$

$G_p$  is also called the spreading factor. This processing gain or spreading factor determines the maximum number of simultaneous users or connections allowed in a communication system. It determines the level of protection against multipath interference signals and signal detection capabilities of a spread spectrum communication system. In multipath situations the receiver observes spread spectrum signals summed with narrowband interference. The processing gain determines the power ratio of the desired

signal and interference after de-spreading. Higher desired signal power leads to easier detection. It can be seen that low data rates such as speech have high processing gain compared to high data rates.

### III. DIRECT-SEQUENCE CDMA

As mentioned CDMA is a spread-spectrum multiple access method. Spread-spectrum is a transmission method in which the signal occupies a bandwidth in excess of the minimum necessary to send the information. The spreading of the signal is accomplished by means of a pseudorandom code that is independent of the transmitted data signal. A synchronized reception with the same pseudorandom code at the receiver is used for de-spreading and subsequent data recovery. [3]

#### A. Principle of DS-CDMA

Figure 2 shows the multiple access capability of a CDMA communication system. Two users are sending simultaneously narrowband information signals having the same bandwidth  $B_i$ . Both narrowband signals are spread with a user specific and unique code having sufficiently low cross-correlation with the other user's code [3]. Code makes each user's communications approximately orthogonal to those of other users. After spreading the two signals are transmitted into a radio channel having the same bandwidth,  $B_t$ . In the radio channel the two signals are mixed and exposed to impairments. Spreading the signal de-sensitizes the original narrowband signal to some potential channel degradation and to interference [3]. The signals cannot be distinguished from each other and from background noise due to their low powers achieved by the spreading. The transmitted energy remains the same, but due to much larger bandwidth, the signal spectrum is often below the noise floor of receivers [3]. At the receiver the desired narrow-band information signal can be extracted or de-spread by a replica of the spreading code used in transmitter for a particular user. Signals for other users are not de-spread; they are spread more.

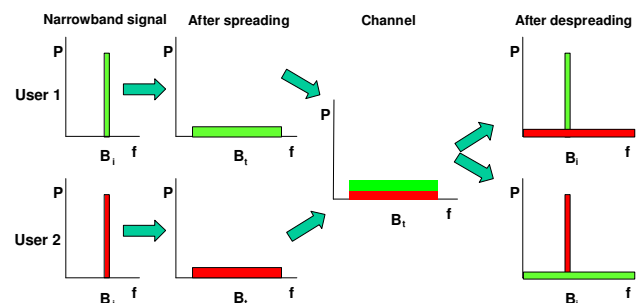
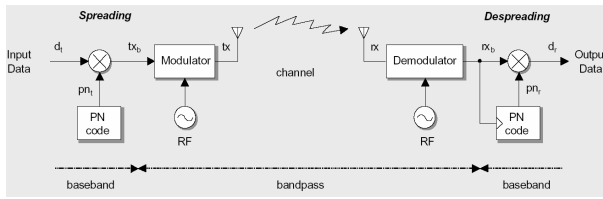


Figure 2. CDMA multiple access principle

#### B. DS-CDMA Transmitter and Receiver

The basic DS-CDMA transmission and reception is illustrated in Figure 3.



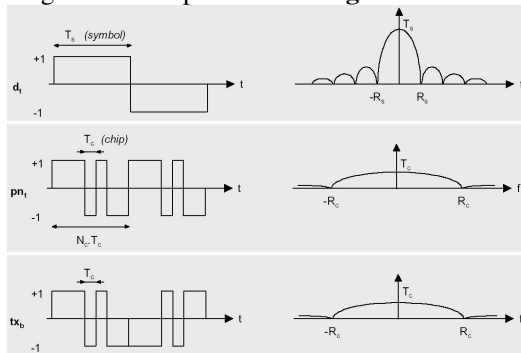
**Figure 3. Transmission and reception in DS-SSM**

Signal transmission consists of the following steps. A pseudo-random code is generated, different for each channel and each successive connection. The information data is spread by pseudorandom code. The resulting signal modulates a carrier. The modulated carrier is amplified and broadcast.

Signal reception consists of the following steps. The carrier is received and amplified. The received signal is mixed with a local carrier to recover the spread digital signal. A pseudo-random code is generated, matching the anticipated signal. The receiver acquires the received code and phase locks its own code to it. The received signal is correlated with the generated code, extracting the information data.

*C. Spreading*

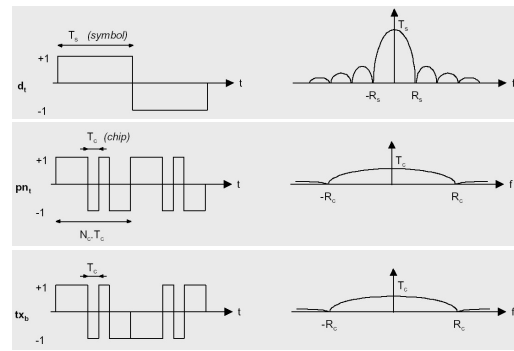
In the transmitter, the binary data is directly multiplied (XOR-function) with the pseudo-noise sequence, which is independent of the binary data, to produce the transmitted baseband signal having much wider bandwidth than the original signal. This is presented in **Figure 4**.



**Figure 4. Spreading in DS-SSM**

*D. De-spreading*

In the receiver the baseband signal is multiplied with the same pseudo-noise sequence. If the pseudorandom code is not the same or it is not in synchronization with the data there is no de-spreading.

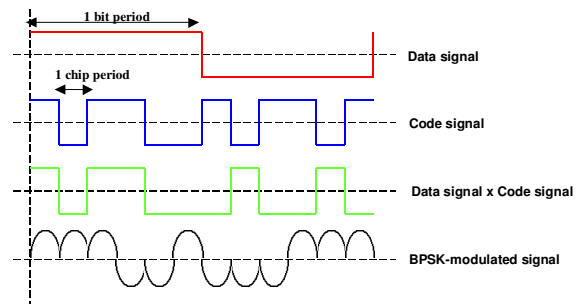


**Figure 5. De-spreading in DS-SSM**

*E. DS Modulation*

Spread-spectrum techniques can be used with many modulations formats, but most practical applications are limited to BPSK (Binary Phase Shift Keying) and QPSK (Quadrature Phase Shift Keying) [3].

Figure 6 shows an example of the generation of a BPSK-modulated spread-spectrum signal. The basic idea is that the signal after the spreading operation i.e. the multiplication is 1 if the two signals are the same, 1 or 0. Otherwise the output is 0. The BPSK-signal has a 180-degree phase shift when the output of the multiplication changes.



**Figure 6. Generation of BPSK-modulated spread spectrum signal**

One advantage of DS modulation is the reduced receiver sensitivity to interference. This advantage is due to the fact that the de-spreading circuit acts as a spreading circuit for any signal to which it is not matched. [3]

*F. Pseudo-Noise Sequences*

The DS-SSM system uses two general categories of spreading sequences: PN sequences and orthogonal codes. The PN sequence is produced by the pseudo-random noise generator that is simply a binary linear feedback shift register, consisting of XOR gates and a shift register. This PN generator has the ability to create an identical sequence for both the transmitter and the receiver, and yet retaining the desirable properties of a noise-like randomness bit sequence.

A PN sequence has many characteristics such as having a nearly equal number of zeros and ones, very low correlation between shifted versions of the sequence and very low cross correlation with any other signals such as interference and noise [3]. However, it is able to correlate very well with itself and its inverse.

Another important aspect is the autocorrelation of the sequence as it decides the ability to synchronize and lock the spreading code to the received signal. This effectively combats

the effects of multipath interference and improves the SNR. M-sequences, Gold codes and Kasami sequences are examples of this class of sequences.

Walsh codes are the most common orthogonal codes used in CDMA applications [4]. These codes correspond to the rows of a special square matrix known as the Hadamard matrix. For a set of Walsh codes of length n, there consists of n rows to form an n x n Walsh code square matrix. The IS-95 system uses a 64 by 64 Walsh function matrix.

Walsh-Hadamard sequences can be used as spreading codes when users are time synchronous. The motivation for the Walsh-Hadamard comes from noting that we can construct  $2^n$  orthogonal sequences of  $2^n$  from sequences of length of  $2^{n-1}$ . Walsh-Hadamard codes will have poor autocorrelation and cross-correlation at time offsets other than zero. [2]

$$\mathbf{H}_n = \begin{vmatrix} \mathbf{H}_{n-1} & \mathbf{H}_{n-1} \\ \mathbf{H}_{n-1} & -\mathbf{H}_{n-1} \end{vmatrix}$$

There are some issues with Walsh codes. Synchronization of all users is required. In a multipath channel, delayed copies may be received which are not orthogonal any longer. Advantages relative to TDMA and FDMA are that no guard bands or guard times are typically required and no equalizer is typically required, when a RAKE receiver is used.

OVSF (Orthogonal Variable Spreading Factor) codes are used in applications that combine messages having different data rates in orthogonal manner. The OVSF codes are defined using a code tree presented in Figure 7.

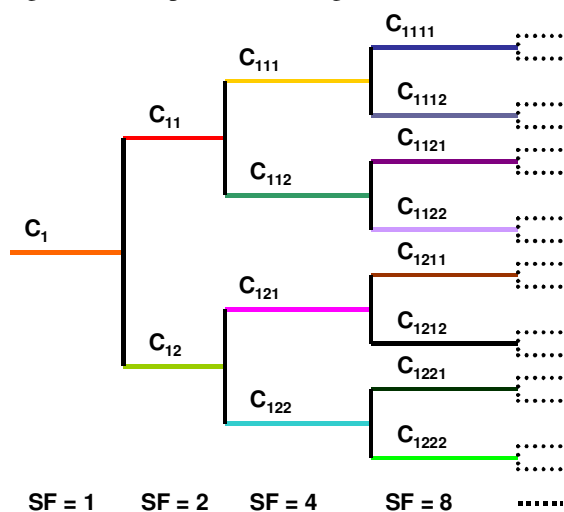


Figure 7. OVSF code tree

IV. CDMA IN CELLULAR ENVIRONMENT

CDMA is a multiple access for wireless communications

based on direct-sequence spread-spectrum. All users can transmit at the same time, and each is allocated the entire available frequency spectrum for transmission. CDMA does not require the bandwidth allocation of FDMA, nor the time synchronization of the individual users needed in TDMA. A CDMA user has full time and full bandwidth available, but the quality of the communication decreases with an increasing number of users.

A. Multiple Access Interference (MAI)

The detector receives a signal composed of the sum of all users' signals, which overlap in time and frequency. MAI refers to the interference between DS users and is a factor, which limits the capacity and performance of the system.

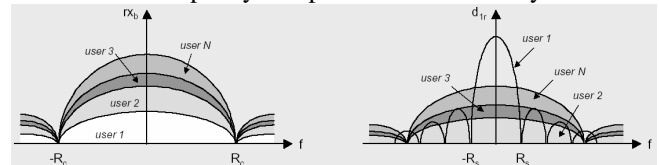


Figure 8. MAI in CDMA

With CDMA systems, the same frequency channel can be used in the adjacent cell, as long as multiple access interference is kept below a given level. This MAI is directly proportional to the channel loading. MAI can be divided in two parts: intra-cell and inter-cell interference. [2]

B. Multipath Channel

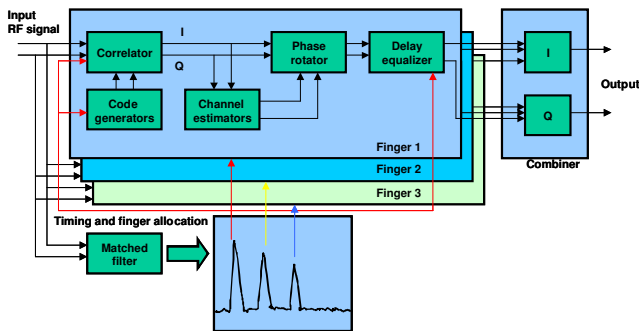
Multipath is the reception of multiple, possibly interfering copies of the same signal. The tolerance of spread-spectrum techniques to interference extends also to a tolerance of multipath. With some receiver designs, multipath can even be used advantageously. [2]

C. RAKE Receiver

Due to reflections from obstacles a wideband radio channel can consist of many copies (multipaths) of originally transmitted signals having different amplitudes, phases, and delays. If the signal components arrive more than duration of one chip apart from each other, a RAKE receiver can be used to resolve and combine them. The RAKE receiver uses a multipath diversity principle. It is like a rake that rakes the energy from the multipath propagated signal components. When a wideband signal is received in a matched filter over a multipath channel, the multiple delays appear at the receiver, as depicted in Figure 10. The RAKE receiver uses several baseband correlators to individually process several signal multipath components. The correlator outputs are combined to achieve improved communications reliability and performance. [1]

Impulse response measurements of the multipath channel profile are executed through a matched filter to make a successful de-spreading. It reveals multipath channel peaks and gives timing and RAKE finger allocations to different receiver blocks. Later it tracks and monitors these peaks with

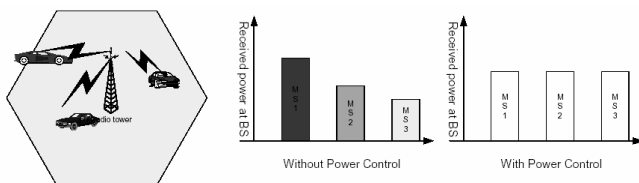
a measurement rate depending on speeds of mobile station and on propagation environment. The number of available RAKE fingers depends on the channel profile and the chip rate. The higher the chip rate, the more resolvable paths there are, but higher chip rate will cause wider bandwidth. To catch all the energy from the channel more RAKE fingers are needed. A very large number of fingers lead to combining losses and practical implementation problems.



**Figure 9. Block diagram of simple RAKE diversity receiver**

#### D. Near-far Problem

Figure 10 illustrates the near-far problem associated with CDMA-based systems. The problem arises when MS A (Mobile Station) and MS B are located in a same cell with different distances from a BS (Base Station). If no power control were applied in uplink, the MS A would transmit so high power that MS B would have no connection to the BS due to too low SIR-values. The MS A would be reserving a great amount of the capacity of the cell. Power control is implemented to overcome the near-far problem and to maximize the capacity of the system [3]. It tries to control the powers of the mobile stations in the system so that the received powers at the base station stay equal. It tries also to compensate the effects of slow fading and fast fading. There is no near-far problem in downlink due to a one-to-many situation. All the signals within one cell originate from the one base station to all mobiles.



**Figure 10. Near-far problem**

#### E. Power Control

Power control is an extremely essential function when considering the smooth operation and the capacity of CDMA-based systems. The power control problem arises due to multiple access interference. Each user looks like random noise to other users and causes unnecessary interference to

the system. That is why the powers of individual users have to be carefully controlled. Power control forces all users to transmit the minimum amount of power needed to achieve acceptable signal quality at the base station. Typically, it reduces the power transmitted by the users closest to the base station, while increasing the power of the users farthest away from the base station. Power control tries to set the power received from all users to be equal at the base station receiver. A secondary reason for power control is to minimize battery consumption in the mobile.

#### F. Soft and Softer Handover

This type of handover is characterized by commencing communications with a new base station on the same CDMA frequency assignment before terminating communications with the old base station. Softer handover occurs between two or more cells of one base station.

A soft and softer handover prevent the ping-pong behavior, and the dual base station capability is a form of diversity that can increase capacity in a heavily loaded system and also coverage in a lightly loaded system. [2] Soft handover helps to minimize with power control the interference both in uplink and downlink directions.

### V. CDMA CAPACITY

In a CDMA-based system capacity can be defined as throughput of bits or as the amount of simultaneous users in the network receiving voice and data services with certain predefined quality targets. Interfering signals caused by users to each other rise, as the amount of users gets higher in the network. A balance between maintaining connection integrity and restricting interference level is maintained by controlling the power of each user so that signals arrive at their intended receiver with minimum required S/N-level. Interference, coverage, and capacity are coupled tightly to together in a CDMA system.

Capacity can be restricted by either transmission power constraints or by the self-generated interference. In the uplink, the system reaches its capacity when a mobile station does not have enough power to overcome interference from the network, or a predefined loading target of the network is met. In the downlink, capacity is reached when no additional power is available to add new users i.e. base station transmission power restrictions are met, or there are no downlink codes available for mobile stations. The power needed for either link is fundamentally related to  $E_b/N_0$  requirements for different services.

#### A. Dynamic Resource

The capacity of different services can change dynamically because  $E_b/N_0$  requirements vary according to changing conditions such as speeds of mobile stations, services, radio channel, and environment. Many factors such as loading, spatial distribution of users, sectorization, service activity, and power control accuracy affect the actual capacity of the network.  $E_b/N_0$  can be defined as in the following equation

$$\frac{E_b}{N_{o_j}} = \frac{W}{\nu_j R_j} \cdot \frac{P_j}{I_{total} - P_j} \quad (2)$$

where  $W$  is the chip rate,  $\nu_j$  is service activity factor,  $R_j$  is the baseband bit rate of a connection  $j$ ,  $P_j$  is received signal power from the connection  $j$ , and  $I_{total}$  is the total received wideband power including thermal noise power in the base station. Solving for  $P$  from previous equation leads to the following equation 3. [6]

$$P_j = \frac{1}{1 + \frac{E_b}{N_{o_j}} \frac{R_j \nu_j}{W}} I_{total} = L_j \cdot I_{total} \quad (3)$$

where  $L_j$  can be defined as the load factor of the  $j$ th mobile user's connection in the uplink direction. For all users in a CDMA network the uplink load factor can be defined as in the following equation 4. [11]

$$\eta_{UL} = \sum_{j=1}^N L_j \quad (4)$$

where  $N$  is the number of uplink connections in the network.

The system has reached its pole capacity when the uplink load factor,  $\eta_{UL}$ , approaches 1. In reality, there are two kinds of interference occurring. Other users in the same cell cause intra-cell interference, and other users in other cells of the network cause inter-cell interference. Inter-cell loading occurs when users from other cells load a cell restricting it from using its whole power capacity for serving users in its coverage area. The effect of inter-cell loading can be taken into account by the ratio of other cell to own cell interference,  $i$ . The uplink load factor then becomes to a formula presented in the following equation 5. First part of the equation defines intra-cell load factor and the second part defines the inter-cell load factor.

$$\eta_{UL} = (1+i) \cdot \sum_{j=1}^N L_j = (1+i) \cdot \sum_{j=1}^N \frac{1}{1 + \frac{E_b}{N_{o_j}} \frac{R_j \nu_j}{W}} \quad (5)$$

Figure 11 presents the uplink pole capacity. The curve has been calculated by inserting different values of load factor in to  $10 \log_{10}(1-\eta_{UL})$  giving the loss or the interference margin in the link budget due to load. As the load factor comes near 1, the interference margin is getting higher quite fast.

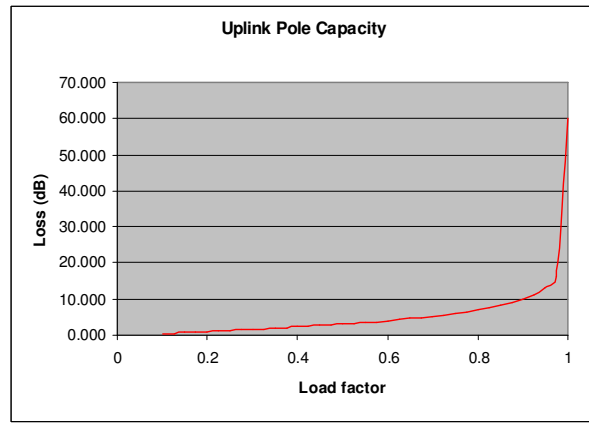


Figure 11. Uplink pole capacity

Typically, load target should be maintained between 50 % and 75 % because at those points the system is stable and can serve users. If the load factor increases, countermeasures such as the Load Control should be executed to stabilize the capacity. This can be done by delaying services or reducing bit rates of those services used by interfering users. [6]

For the downlink the load factor is quite similar to the uplink, but some parameters have to be defined. The following equation 6 presents the downlink load factor.

$$\eta_{DL} = \sum_{j=1}^N \nu_j \cdot \frac{N_{o_j}}{W} \frac{E_b}{R_j} [1 - \alpha_j] + i_j \quad (6)$$

where  $\alpha_j$  is the orthogonality factor in the downlink. Orthogonal codes are employed in CDMA-based systems to separate the users. The situation would be simple if there were no multipaths. The orthogonality would then remain when the mobile receives the signal from the base station. However, if there is a too short or a too long delay spread in the radio channel, the mobile will see part of the base station signal as multiple access interference. A too short delay spread means that the time difference between multipaths is less than 0.26ms, and the RAKE receiver cannot combine them coherently to obtain multipath diversity. A too long delay spread means that some multipaths do not fit into the measurement window of the matched filter in the RAKE receiver. If  $\alpha_j = 1$ , then the base station signals are perfectly orthogonal, but in real multipath radio channel the orthogonality factor is typically between 0.4 and 0.9; larger in microcells than in macrocells. The ratio of other cell to own cell interference,  $i_j$ , depends on the user location and is therefore different for each user  $j$ . This can lead a to a very dynamically changing downlink load factor. [6]

## VI. CDMA CELLULAR APPLICATIONS

Cellular wireless communications have evolved from first generation analog techniques to the more flexible second and third generation digital techniques that are currently employed. Future developments are aimed at further

enhancing these digital techniques to integrate voice, messaging, and high-speed data. For CDMA following cellular standards are shortly introduced. All standards use the basic CDMA procedures such as pilot channel, RAKE receiver, power control and soft handover presented earlier.

#### A. IS-95A and IS-95B

The IS-95A standard was finished in 1993 and first commercially launched in 1996 primarily for cellular voice communication. The basic data rate is 9,6 kbps (max 14,4 kbps) and the data is direct-sequence-spread to a chip rate of 1.2288 megachips per second. The allocated bandwidth is 1.25 MHz. [4]

The IS-95B is packet data enhancement to IS-95A like GPRS is to GSM system. IS-95B or as called "cdmaOne" was commercially launched in 1999 with data rates up to 115,5 kbps.

IS-95 uses fixed spreading code of length 64; repeating bits provides lower data rates. IS-95 system uses pilot channel in downlink direction to provide synchronization, channel tracking, and handover functions. In the uplink direction, orthogonal modulation is used, which permits the more robust noncoherent demodulation to be used.

In IS-95, all base stations use the same scrambling code (short code) to distinguish among their transmissions, but with different timing offsets. GPSS receiver in every base station provides base station synchronization.

#### B. CDMA2000 1X and Future Evolution

CDMA2000 1X is the third generation evolution phase of IS-95A/B and it can offer up to 307 kbps data rates. CDMA2000 can use same 1.25 MHz as IS-95/cdmaOne. Also there is 1xEVDO (Data Only) and 1xEVDO (Data&Voice) that can offer high-speed data rates from 2,4 Mbps to 3,09 Mbps. These enhancements can be compared to HSDPA (High Speed Downlink Packet Access) in WCDMA standard in Europe.

#### C. WCDMA

WCDMA increases chip rate by more than a factor of three, and the channel bandwidth a factor of four, compares to IS-95. The faster chip rate (3,84 Mchips/s) implies that WCDMA receiver can provide greater multipath resolution, and with a RAKE receiver, this implies greater frequency diversity. [2]

WCDMA provides different data rates up to 384 kbps for circuit switched and up to 2 Mbps for packet switched data with OVSF codes. On the downlink, the spreading factor can be from 4 up to 512 and in the uplink from 4 to 256. [6]

WCDMA employs coherent detection on both uplink and downlink direction by using pilot bits in transmission. In WCDMA, a specially formatted synchronization channel has the information embedded in it that determines the timing offset of the local base station.

## VII. CONCLUSION

This paper has introduced direct-sequence spread-spectrum basics and pointed out some important CDMA cellular requirements on DS-SS. DS-CDMA is probably the most interesting multiple access method provided by spread-spectrum technology. In DS-CDMA data is scrambled by user specific pseudo-noise code at the transmitter. The effect of interference can be reduced by the processing gain. Through RAKE receiver multipaths can be used in advantage to improve receiver performance by capturing the energy in paths having different transmission delays. In fading channels, by use of the RAKE receiver, a SS receiver can obtain an important advantage in diversity.

When considering cellular CDMA system some aspects are really important. Power control and soft handover must work or there is no cellular CDMA as we know. Interference, coverage, and capacity are coupled tightly to together in CDMA systems.

Nowadays systems such as CDMA2000 and its evolution versions, and European WCDMA are becoming more and more popular as the networks are opening commercially around the world. The third CDMA era is now starting.

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## HOMEWORK

1. a) Construct Walsh-Hadamard sequences of length of 8 if

$$\mathbf{H}_1 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

- b) Spread following data signal, S, with 3<sup>rd</sup> row sequence of the Walsh-Hadamard matrix constructed in phase a)

$$S = [1 \ -1 \ -1 \ 1]$$

2. Why are power control and soft handover so important features in CDMA cellular systems?