C D M A

Code Division Multiple Access

Tommi Heikkilä

Agenda

- Introduction
- History of Spread-Spectrum and CDMA
- Introduction to DS-CDMA
- Cellular CDMA
- CDMA Capacity
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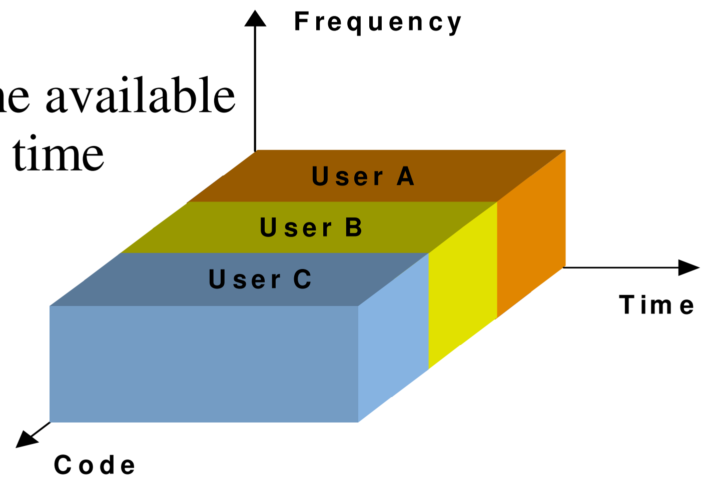
Introduction

- CDMA is a modulation and multiple access scheme based on the spread-spectrum communication technology
- Individual terminals use spread-spectrum techniques and occupy the entire spectrum whenever they transmit
  - Users share time and frequency allocations, and are channelized by unique assigned codes
  - 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
- In FDMA each user is given a small portion of the total available spectrum
- In TDMA each user is allowed full use of the available spectrum, but only during certain periods in time



History of Spread-Spectrum and CDMA

- Development of the CDMA technique dates back to the early 1950s when different studies of the spread-spectrum technologies were started
- Basic 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
- In 1970s several military and navigation applications were developed.
  - Military with very low C/I, Anti-jamming applications
- Cellular applications proposed late 70s focused on narrowband systems
  - In 1978 Cooper and Nettleton suggested a cellular spread-spectrum application
- During 80s Qualcomm investigated CDMA for cellular applications
  - IS-95 standard 1993 and commercial networks introduced in 1995
- 3G wideband CDMA systems, such as CDMA IS-2000 and European WCDMA developed from 1990s and still going on
  - Commercial networks are opened at the moment

Spread-Spectrum Technology (1)

- Originally developed for military and navigation purposes
  - secure means of communication in hostile environments
  - Low Probability of Interception
    - Cannot be easily detected by enemy communication equipment due to low power spectral density, even lower than background noise
  - Anti-Jamming
    - Properties to combat intentional interference trying to sabotage communication systems
- Nowadays 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
  - DS-CDMA is probably the most interesting multiple access method provided by spread-spectrum technology

Spread-Spectrum Technology (2)

- Transmission bandwidth is much larger than information bandwidth
- Bandwidth does not depend on the informational signal
- Processing gain = Transmitted bandwidth/ Information bandwidth

$$G_p = \frac{B_t}{B_i}$$

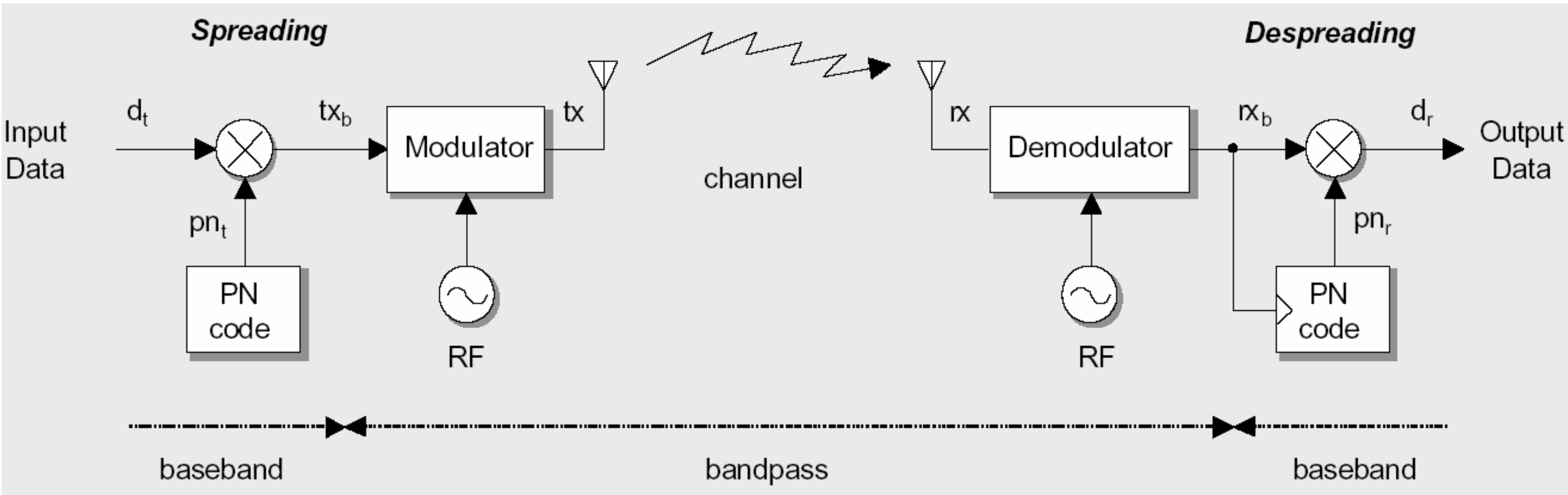
  - Gp is also called the spreading factor and determines the maximum number of simultaneous users or connections allowed in a communication system
  - Determines the level of protection against multipath interference signals and signal detection capabilities of a spread spectrum communication system
  - In multipath situations the receiver observes spread-spectrum signals summed with narrowband interference
  - Determines the power ratio of the desired signal and interference after de-spreading
  - Low data rates such as speech have high processing gain compared to high data rates
  - High data rate means less processing gain and higher transmit power or smaller coverage

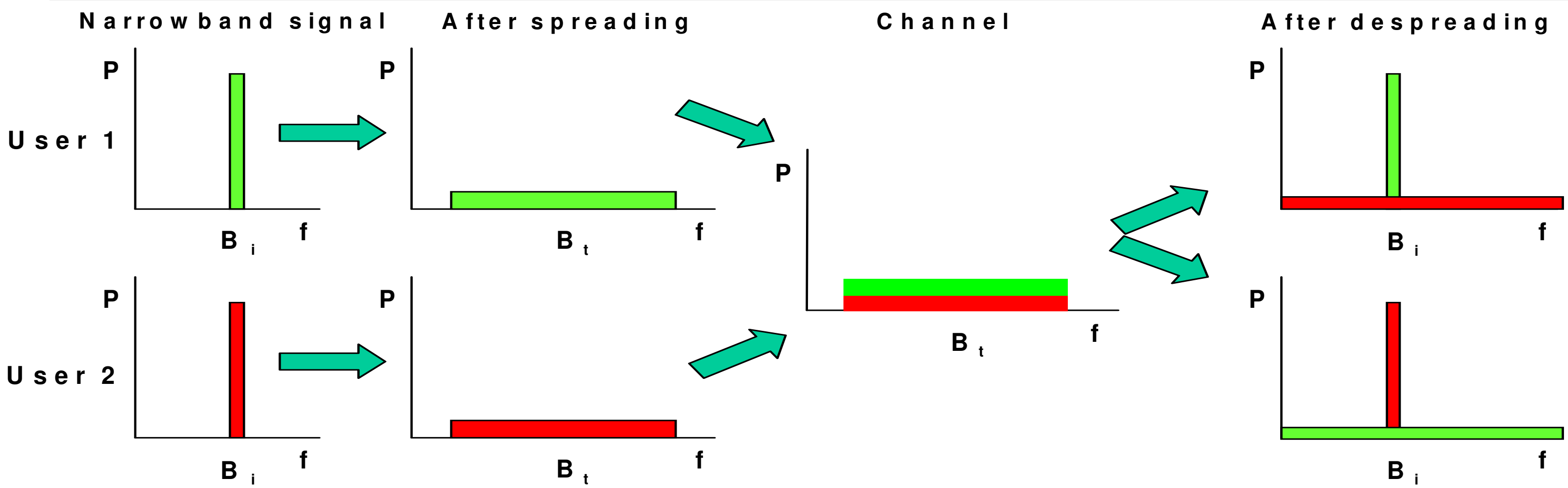
Spread-Spectrum Technology (3)

- Classification of Spread Spectrum technologies
  - Direct-Sequence
    - Data is scrambled by user specific pseudo noise code at the transmitter side
  - Frequency Hopping: The signal is spread by changing the frequency over the transmitted time of the signal:
    - Fast frequency hopping
    - Slow frequency hopping
  - Time Hopping
    - The data is divided into frames, that itself are divided into time intervals
    - The data is burst is hopped over the frames by utilising code sequences
- Also, a variety of hybrid techniques use different combinations of these two basic techniques

Introduction to DS-CDMA (1)

DS-CDMA transmission and reception

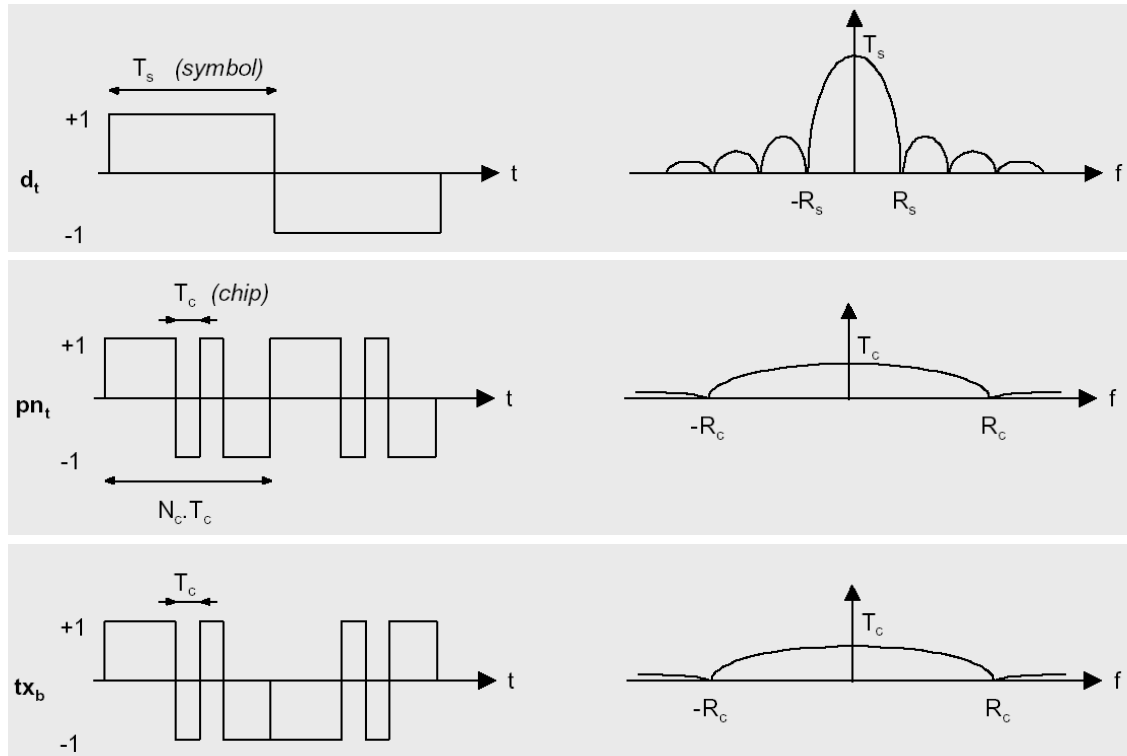




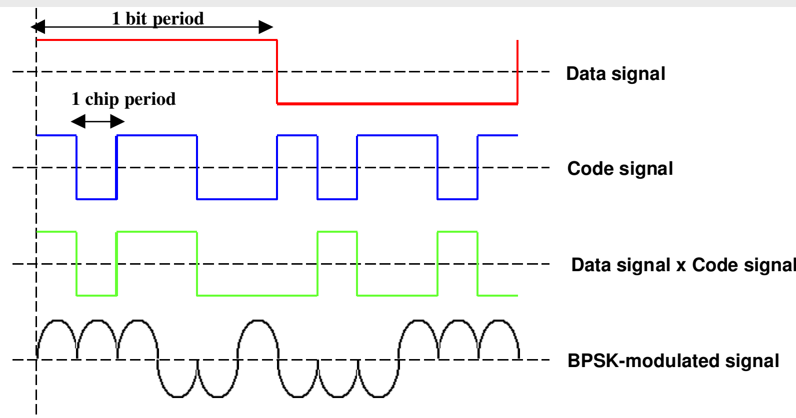
Introduction to DS-CDMA (2)

Spreading

- A pseudo-random code is generated, different for each channel and each connection
- The information data is spread by a pseudorandom code



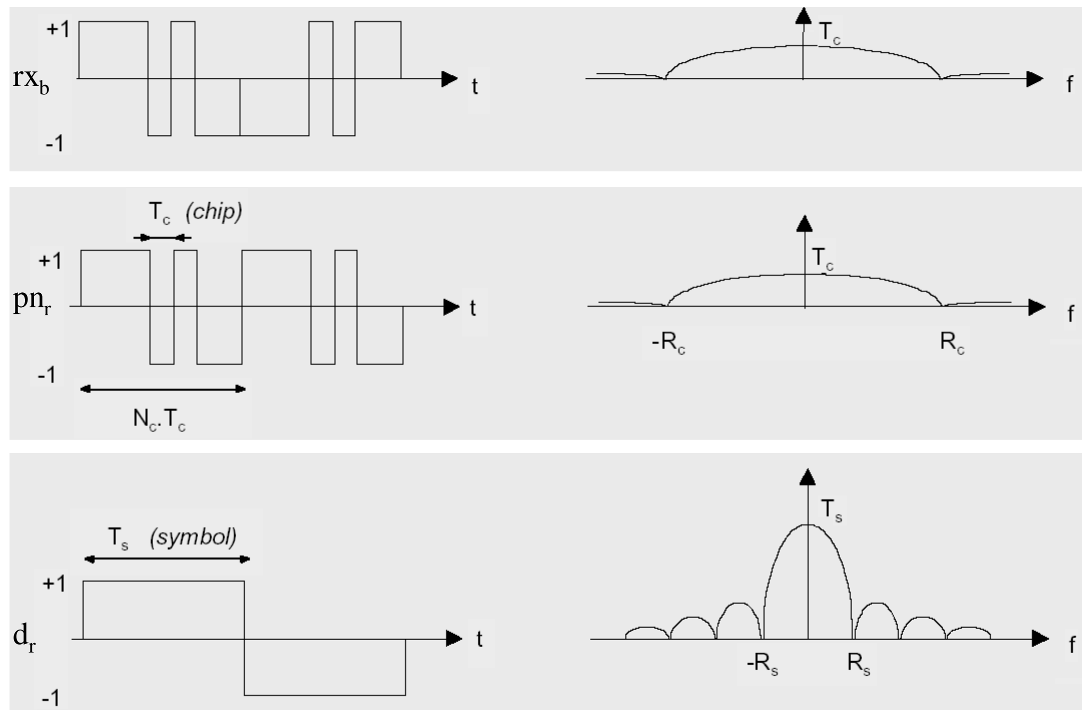
- The resulting signal modulates a carrier
- BPSK-signal has a 180-degree phase shift when the output of the multiplication changes.



Introduction to DS-CDMA (3)

De-spreading

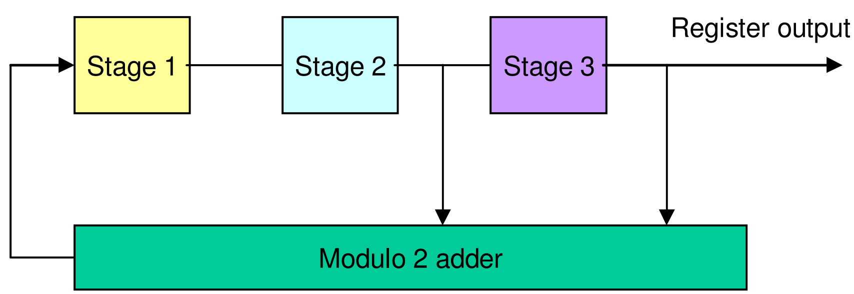
- A pseudo-random code is generated, matching the anticipated signal
- The receiver acquires the received code and phase locks its own code to it
- The received signal is correlated with the generated code, extracting the information data



Introduction to DS-CDMA (4)

Pseudo-Noise (PN) sequences

- Produced by the pseudo-random noise generator that is simply a binary linear feedback shift register, consisting of XOR gates and a shift register
  - Ability to create an identical sequence for both the transmitter and the receiver
  - properties of a noise-like randomness bit sequence
- PN sequences have characteristics such as
  - Nearly equal number of zeros and ones
  - Low correlation between shifted versions of the sequence
  - Low cross-correlation with other user signals (interference) and noise
  - Good autocorrelation properties with own signal in synchronisation
- M-sequences, Gold codes and Kasami sequences are examples of PN sequences



Introduction to DS-CDMA (5)

Walsh Codes

- Walsh codes are the most common orthogonal codes used in CDMA
- Correspond to the rows of matrix known as the Hadamard matrix
- Walsh-Hadamard sequences can be used as spreading codes when users are time synchronous
  - The IS-95 system uses a 64 by 64 Walsh function matrix
- The motivation for the Walsh-Hadamard comes from noting that we can contruct 2^n orthogonal sequences of 2^n from sequences of length of 2^{n-1}

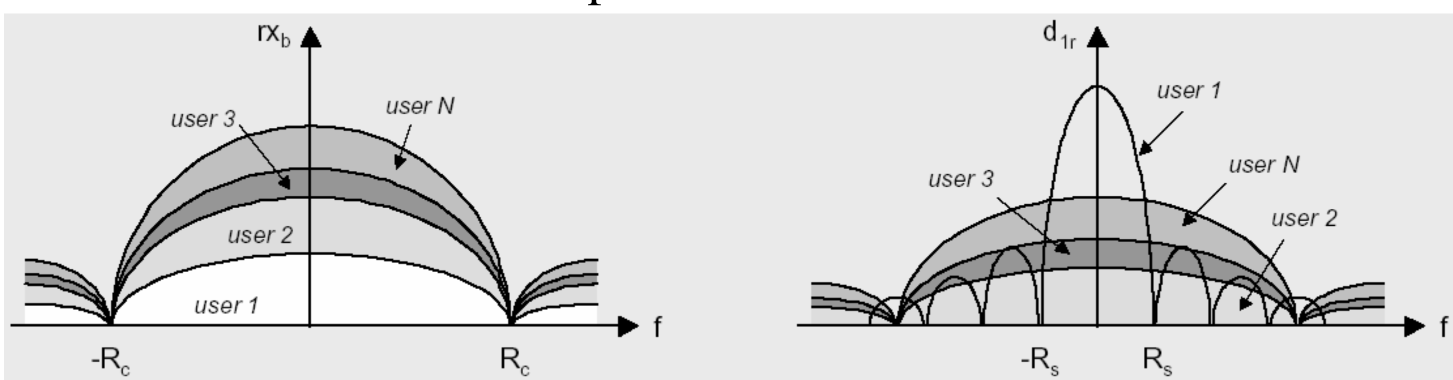
$$\mathbf{H}_n = \begin{vmatrix} \mathbf{H}_{n-1} & \mathbf{H}_{n-1} \\ \mathbf{H}_{n-1} & -\mathbf{H}_{n-1} \end{vmatrix}$$

- Walsh-Hadamard codes will have poor autocorrelation and cross-correlation at time offsets other than zero
  - Synchronization of all users is required
  - In a multipath channel, delayed copies may be received which are not orthogonal any longer
  - RAKE receiver is needed

Cellular CDMA (1)

Multiple Access Interference (MAI)

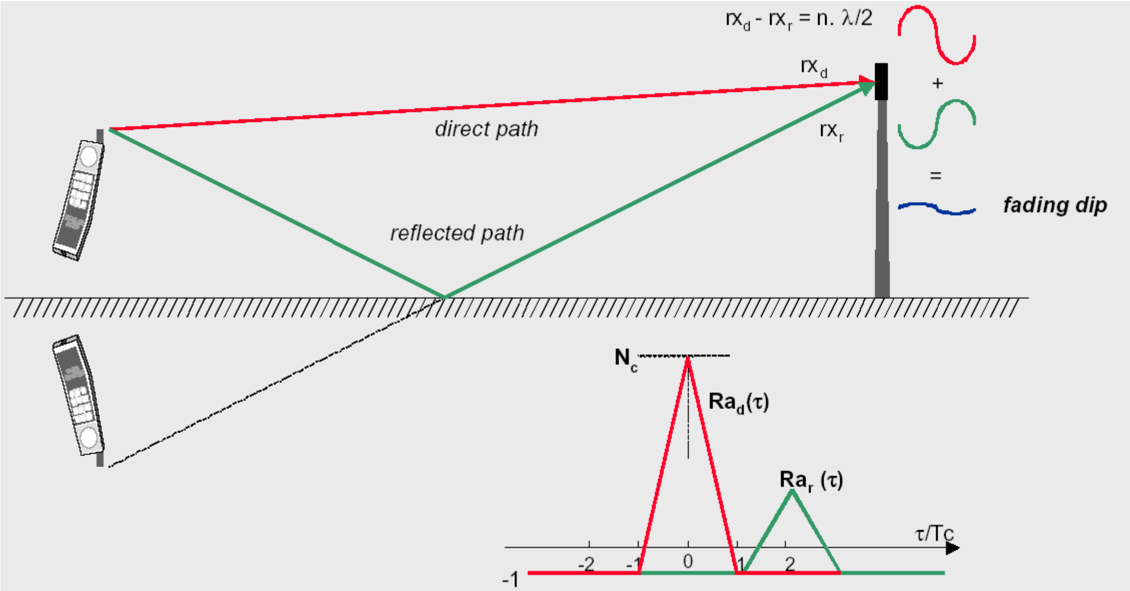
- The detector receives a signal composed of the sum of all users' signals, which overlap in time and frequency
- MAI refers to the interference between users and is a factor, which limits the capacity and performance of the system
- With CDMA systems, the same frequency channel can be used in the adjacent cell, as long as multiple access interference is kept below a given level
- MAI is directly proportional to the channel loading
- MAI can be divided in two parts: intra-cell and inter-cell interference



Cellular CDMA (2)

Multipath

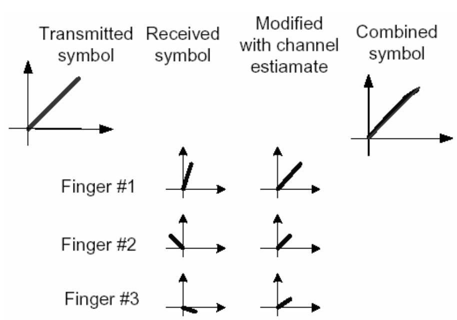
- Reception of multiple, possibly interfering copies of the same signal
  - Atmospheric reflection or refraction
  - Reflections from ground, buildings, or other objects
- The tolerance of CDMA to interference extends also to a tolerance of multipath

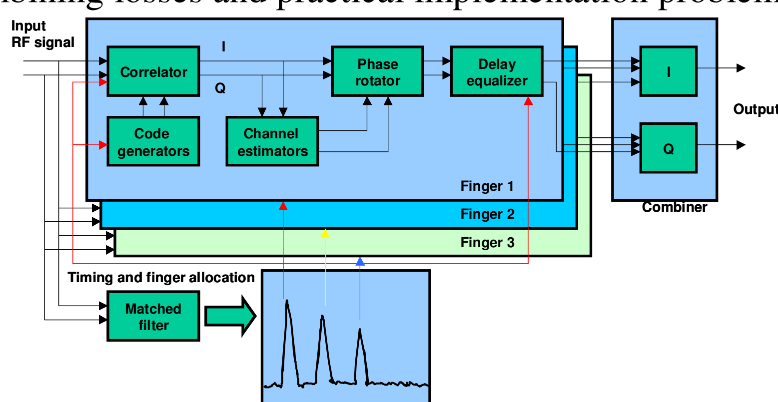


Cellular CDMA (3)

RAKE receiver

- Uses a multipath diversity principle
  - Uses several baseband correlators to individually process several signal multipath components
  - Correlator outputs are combined to achieve improved communications reliability and performance
- 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
  - Tracks and monitors these peaks with a measurement rate depending on speeds of mobile station and on propagation environment
- Number of available fingers depends on the channel profile and the chip rate
  - The higher the chip rate, the more resolvable paths there are
  - A very large number of fingers lead to combining losses and practical implementation problems

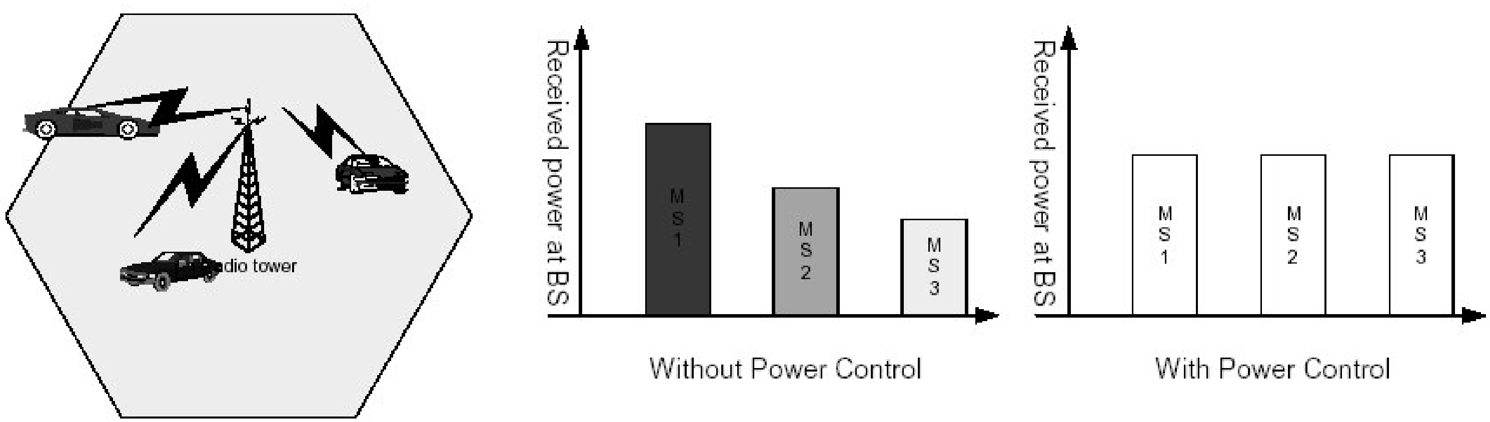




Cellular CDMA (4)

Near-Far Problem

- The problem arises when MS A and MS B are located in a same cell with different distances from a BS
- 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



Cellular CDMA (5)

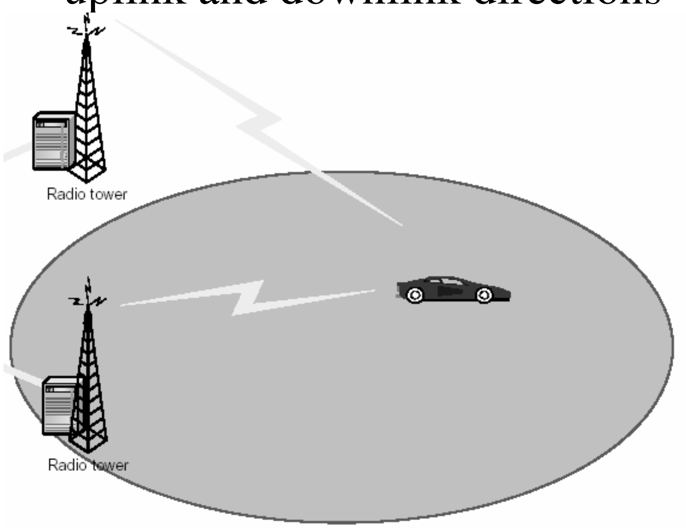
Power Control

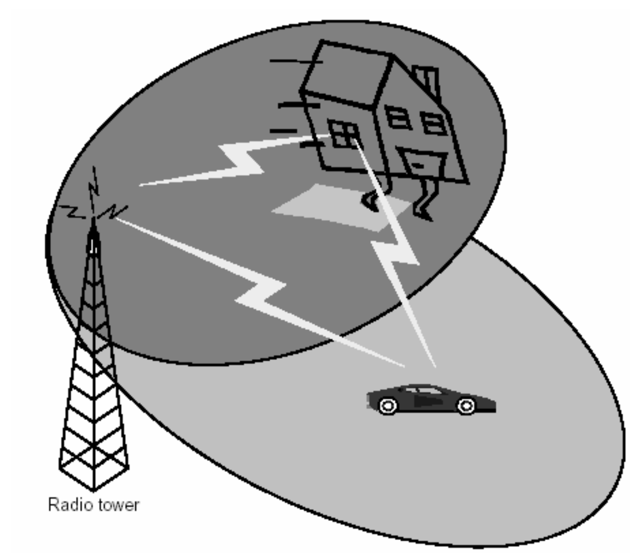
- Power control is an extremely essential function when considering the smooth operation and the capacity of CDMA-based systems
- The power control problem arises due to multiple access interference
- Each user looks like random noise to other users and causes unnecessary interference to the system
- Power control is implemented to overcome the near-far problem and to maximize the capacity of the system
  - 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
- Power control forces all users to transmit the minimum amount of power needed to achieve acceptable signal quality at the base station

Cellular CDMA (6)

Soft and Softer Handover

- 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
- Soft handover helps to minimize with power control the interference both in uplink and downlink directions





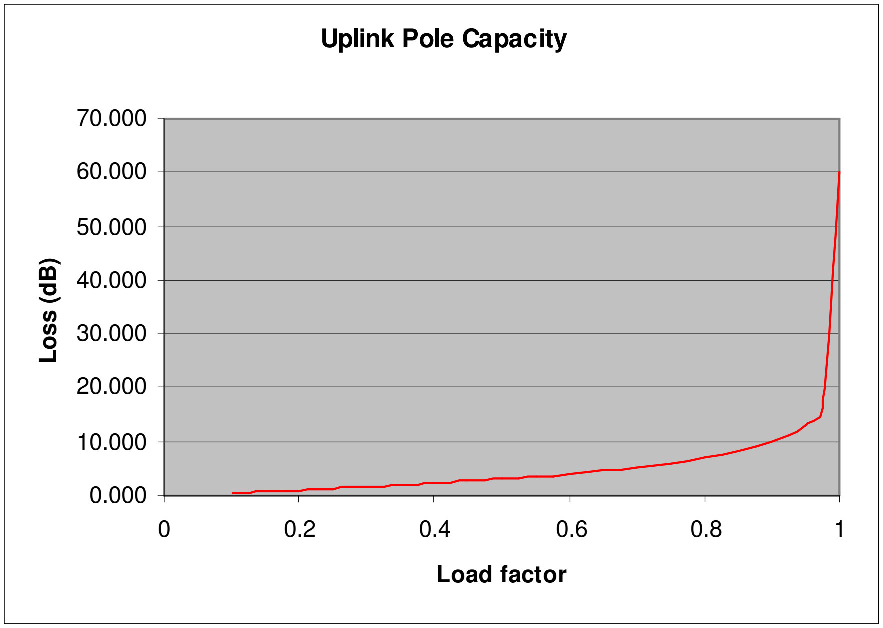
CDMA Capacity (1)

- 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 SIR-level
- Interference, coverage, and capacity are coupled tightly to together
- 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
  - The power needed for either link is fundamentally related to Eb/No requirements for different services

CDMA Capacity (2)

- Eb/No can be defined as in the following equation
$$\frac{E_b}{N_0}_j = \frac{W}{\upsilon_j R_j} \cdot \frac{P_j}{I_{total} - P_j}$$
- Where W is the chip rate, υ_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
$$P_j = \frac{1}{1 + \dfrac{W}{\frac{E_b}{N_o}_j R_j \upsilon_j}} I_{totql} = L_j \cdot I_{total}$$
  - where L_j can be defined as the load factor of the jth 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
$$\eta_{UL} = \sum_{j=1}^{N} L_j$$
  - where N is the number of uplink connections in the network
- The system has reached its pole capacity when the uplink load factor, η_{UL}, approaches 1. In reality, there are two kinds of interference occurring. 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
$$\eta_{UL} = (1+i) \cdot \sum_{j=1}^{N} L_j = (1+i) \cdot \sum_{j=1}^{N} \frac{1}{1 + \dfrac{W}{\frac{E_b}{N_o}_j R_j \upsilon_j}}$$

CDMA Capacity (3)



- The curve has been calculated by inserting different values of load factor in to 10log10(1-η_{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.
- Typically, load target should be maintained between 50 % and 75 % because at those points the system is stable and can serve users.

CDMA Capacity (4)

- For the downlink the load factor is quite similar to the uplink

$$\eta_{DL} = \sum_{j=1}^{N} \upsilon_j \cdot \frac{\left(\frac{E_b}{N_o}\right)_j}{\frac{W}{R_j}} \left[(1-\alpha_j) + i_j \right]$$

  - where α_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 as orthogonality would then remain when the mobile receives the signal from the base station
- 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

CDMA Cellular Applications (1)

IS-95

- Standard was finished in 1993 and first commercially launched in 1996
- Basic data rate is 9,6 kbps
- Chip rate of 1.2288 Mchips/s
- Allocated bandwidth is 1.25 MHz
- The IS-95B is packet data enhancement like GPRS is to GSM system
  - “cdmaOne” was launched in 1999 with data rates up to 115,5 kbps

- Fixed spreading code of length 64; repeating bits provides lower data rates
- 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.

CDMA Cellular Applications (2)

CDMA2000

- The third generation evolution phase of IS-95A/B
- It can offer up to 307 kbps data rates (compare to EDGE)
- CDMA2000 can use same 1.25 MHz as IS-95/cdmaOne

1xEV-DO/DV

- 1xEVDO (Data Only) and 1xEVDV (Data&Voice)
- Can offer high-speed data rates from 2,4 Mbps to 3,09 Mbps

WCDMA

- The faster chip rate of 3,84 Mchips/s implies that WCDMA receiver can provide greater multipath resolution and with a RAKE receiver, this implies greater frequency diversity due to wider bandwidth, 5 MHz
- Data rates up to 384 kbps for circuit switched and up to 2 Mbps for packet switched data
- Downlink spreading factor = 4 - 512 and uplink spreading factor = 4 - 256.
- Coherent detection on both uplink and downlink direction by using pilot bits in transmission
- HSDPA 3GPP R5 using new modulation (QPSK+16QAM) and coding schemes to give higher data rates for packet switched data in WCDMA

Conclusions

- DS-CDMA is probably the most interesting multiple access method provided by spread-spectrum technology
- Data is scrambled by user specific pseudo noise code at the transmitter
- Through RAKE receiver multipaths can be used in advantage to improve receiver performance by capturing the energy in paths having different transmission delays
- 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, its evolution versions, and European WCDMA are becoming more and more popular as the networks are opening commercially around the world

References

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Homework

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

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

1. b) Spread following data signal, S, with 3rd 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?