展頻通訊
(Spread Spectrum Communications)

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CDMA
(Code Division Multiple Access)

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- CDMA systems
- Near/Far Problem
- Power Control
- System Capacity
- RAKE Receiver
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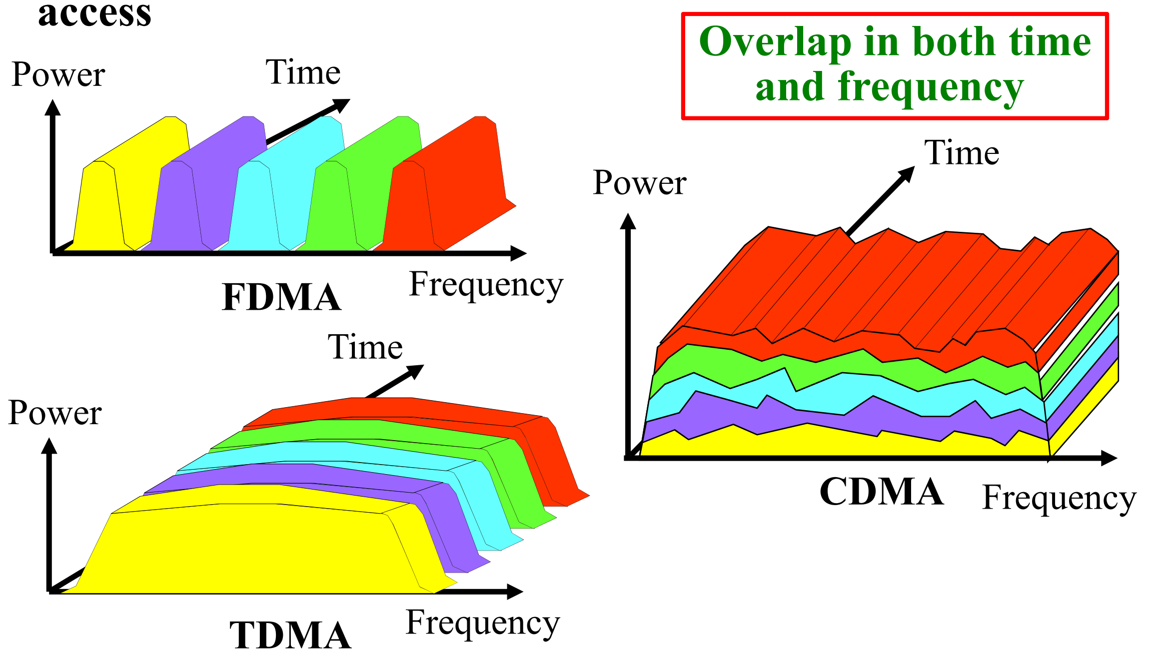
Concepts of CDMA

Multiple Access Techniques

- **FDMA:** Frequency Division Multiple Access
  - Divide a frequency band into multiple sub-bands
  - Generally, a **guard band** between two contiguous sub-bands is required
  - Generally, no **self-interference** is introduced
- **TDMA:** Time Division Multiple Access
  - Divide a time interval (frame) into multiple time-slots
  - A **guard time** between two contiguous time-slots is required
  - Generally, no **self-interference** is introduced
- **CDMA:** Code Division Multiple Access
  - Divide the spectral resource in the **code domain**
  - A set of low **cross-correlation** codes is needed
  - **Self-interference** is introduced among different signals

Multiple Access Techniques (Cont.)

- CDMA can be regarded as a kind of **non-orthogonal multiple access**



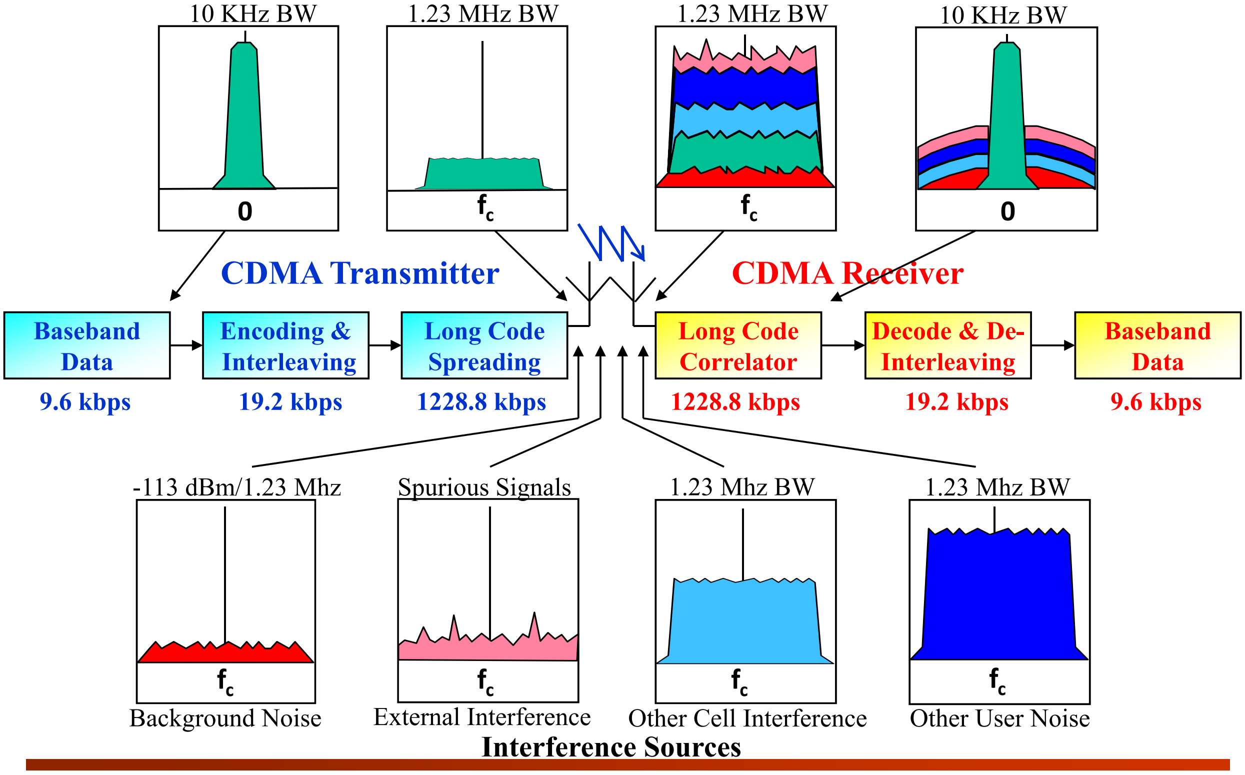
Code Division Multiple Access

- **Code division multiple access** (**CDMA**) is
  - A form of multiplexing and
  - A method of multiple access
- CDMA encodes data with a special code associated with each channel, and uses the constructive properties of the special codes to perform the multiplexing.
  - CDMA does not divide up the channel by **time** (TDMA) or **frequency** (FDMA)
  - Different channels are distinguished by different **spreading codes** (DSSS) or different **hopping patterns** (FHSS)

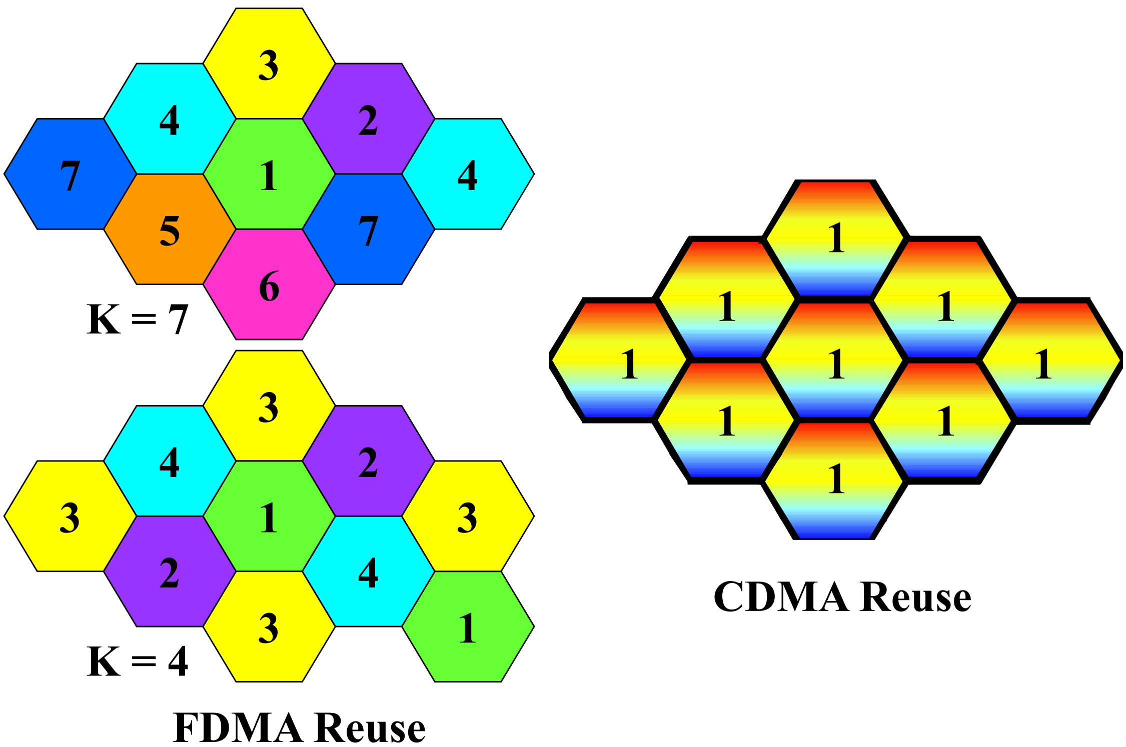
Code Division Multiple Access (Cont.)

- The desired signal is firstly spread by the spreading code(s) and then transmitted over the wireless channel
- **Multiple access interference** (MAI) and the channel noise are added to the desired signal in the channel
- At the receiver, the code generator is synchronized with the desired signal
- Then the desired signal is despread to a narrow band signal by using the corresponding spreading code(s)

CDMA Systems



Cellular Frequency Reuse Patterns



Spreading Codes for CDMA

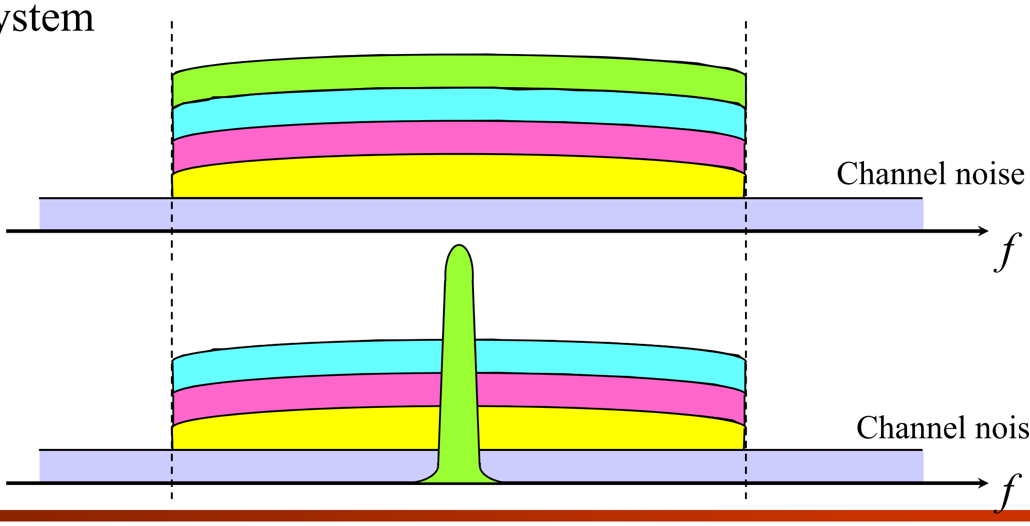
- **How to discriminate different signals?**
  - Discriminate different signals from the serving (same) cell
  - Discriminate the signals from different cells
- Some codes are available for CDMA systems:
  - **Orthogonal codes**:
    - Excellent cross-correlation properties for different signals
    - Sensitive to synchronization
  - **Quasi-orthogonal codes**:
    - Good or acceptable cross-correlation properties for different signals
    - Not sensitive to synchronization

Spreading Codes for CDMA (Cont.)

- For all **downlink** channels transmitted by the same BS:
  - **Timing synchronization** can be easily maintained
  - **Orthogonal codes** (such as Walsh codes) are used to discriminate different signals from the serving cell
  - Due to **multipath propagation**, the orthogonality is partly **destroyed** ⇒ MAI from the serving cell
- For all **uplink** channels:
  - Timing synchronization is **impossible**
  - **Quasi-orthogonal codes** are generally used to discriminate the signals from different users
- For signals from **different cells**:
  - Timing synchronization is **impossible**
  - **Quasi-orthogonal codes** are generally used

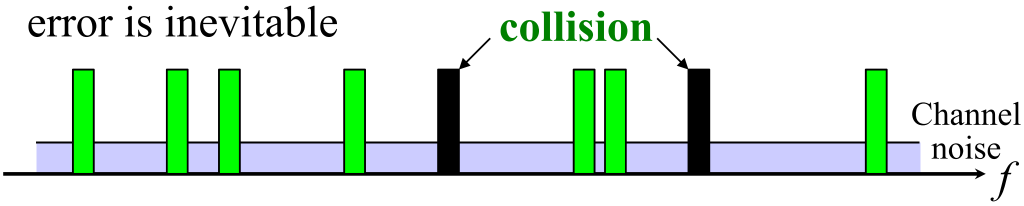
DSSS Multiple Access

- For DSSS CDMA systems, different signals occupy the same frequency band.
- Increasing the number of simultaneous users will raise the **MAI** power spectrum density ⇒ An **interference-limited** system



FHSS Multiple Access

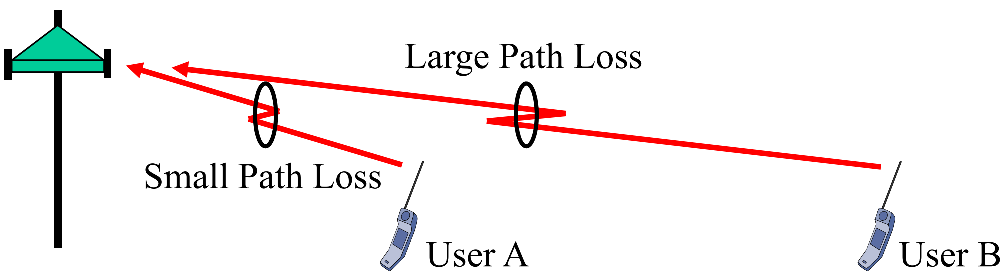
- For FHSS CDMA systems, a signal only occupies **a narrow band channel** at a time instant
  - If no collision occurs, there is **no interference**
  - If a collision occurs, a very **strong** interference is introduced
- Increasing the number of simultaneous users will raise **the probability of collision** ⇒ An **interference-limited** system
- If an effective **channel coding** scheme is applied to data transmission, the effect caused by collision could be eliminated
  - However, if **the probability of collision** is too high, data error is inevitable



Near-Far Problem

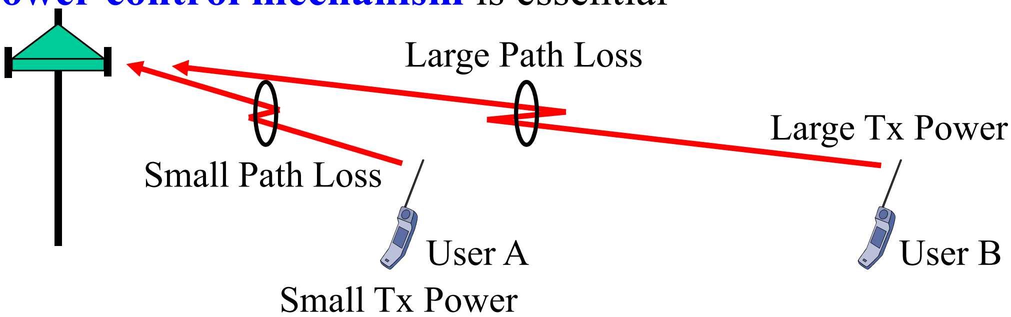
Near-Far Problem

- The existence of the **near-far problem** is mainly due to that different users share the same frequency band at the same time
- The desired signal power of a specific user is the **interference** to other co-channel users
- If both users have the same transmission power, the signal of user B will be strongly interfered by the signal of user A



Near-Far Problem (Cont.)

- The signal of a near-field user has a very small path loss
  - A very large signal power is received in the serving BS
- The signal of a far-field user suffers a very large path loss
  - A very small signal power is received in the serving BS
- The power difference may be larger than **40 dB**
  - The processing gain cannot overcome the power difference
- **Power control mechanism** is essential

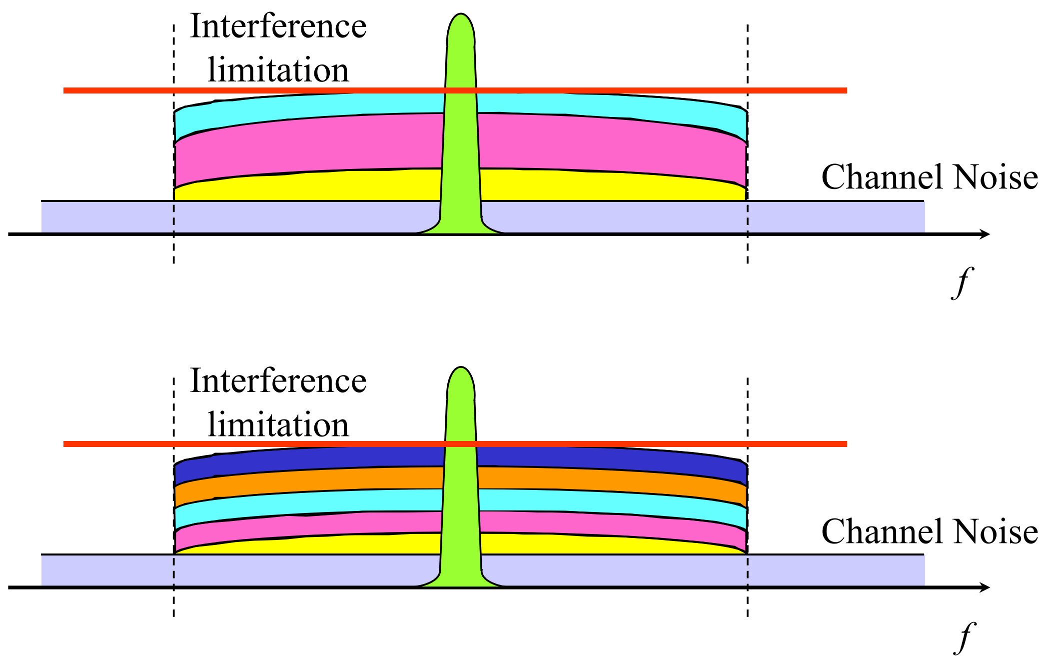


Power Control

Power Control Mechanism

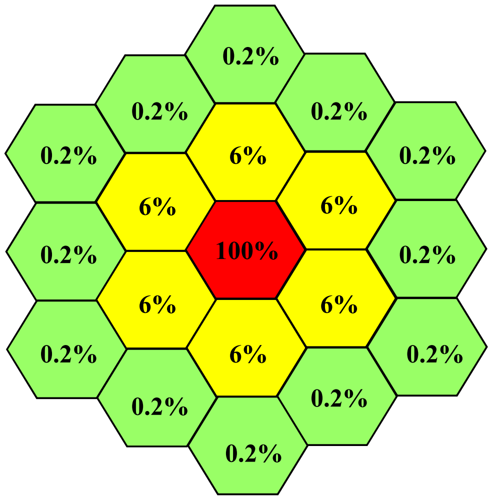
- Two issues are considered in the power control mechanism:
  - The received **signal power**
  - The received **signal quality** (carrier-to-interference power ratio (CIR) or the decoded output quality (frame error rate))
- Considering the received signal power: A user suffers from a large path loss should have a large transmission power
- Considering the received signal quality: A user suffers from a large interference power should have a large transmission power
- A good power control mechanism can improve the **link quality** and the **system capacity**

Power Control and System Capacity



Power Control Mechanism – Up-link

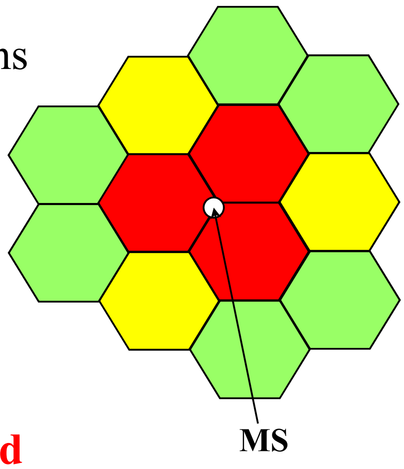
- For **reverse-link/up-link** channels:
  - All up-link channels have the same desired receiver (i.e., the serving BS)
  - The major co-channel interference comes from all the MS **in the same cell**
  - The goal is to control different channels in the same cell having **the same received signal power** at the serving BS
    - **Prevent the near-far problem**



Co-channel interference for up-link channels

Power Control Mechanism – Down-link

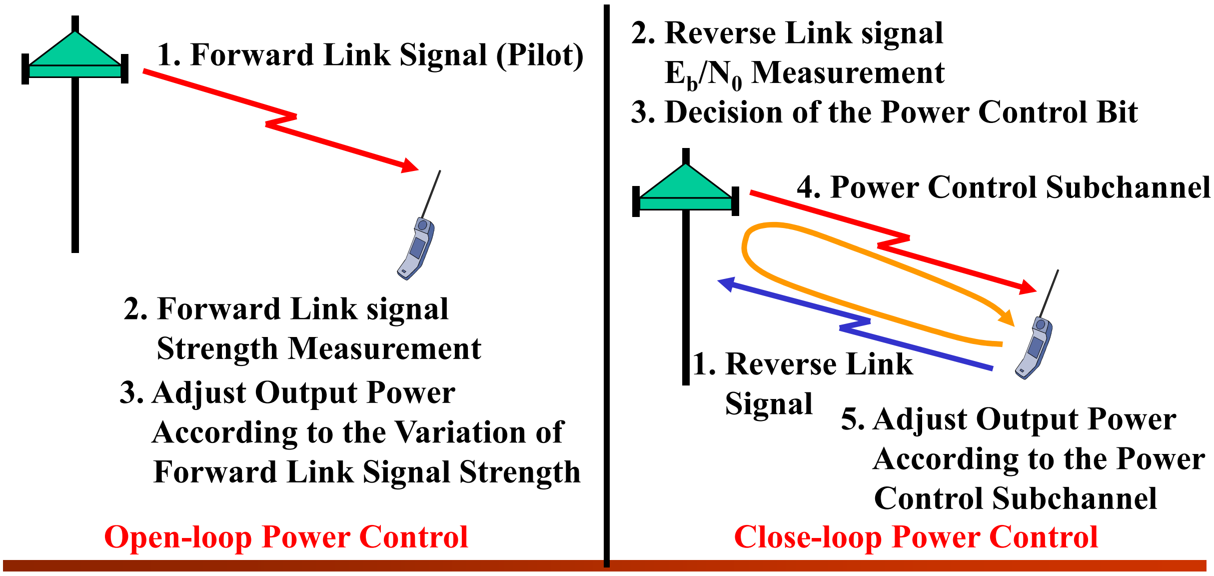
- For **forward-link/down-link** channels:
  - Different down-link channels have different receivers at different locations
  - Due to the employing of orthogonal codes in a cell, the major co-channel interference comes from **the serving cell and all neighboring BSs**
    - Depends on the propagation environment and the location
  - The goal is to control that **the received CIR** at the desired level
    - The allocated transmission power depends on the **interference level**



Co-channel interference for down-link channels

Power Control Mechanism Classification

- The PC mechanism can be divided into two categories:
  - **Open-loop**: feedback is not required
  - **Close-loop**: feedback is required



Power Control Mechanism – Open-loop

- Open-loop power control:
  - Usually applied in the **up-link** channels
  - According to the variation of the **received pilot signal power**
  - Executed solely by the MS
  - Adjust the average transmission power to compensate the variation due to **large-scale fading** (path loss & shadowing)
  - Provide a slow power control mechanism with **a very large dynamic range** per step
- When the received **pilot signal** power increases (or decreases)

  $\Rightarrow$ The propagation loss is decreasing (or increasing)

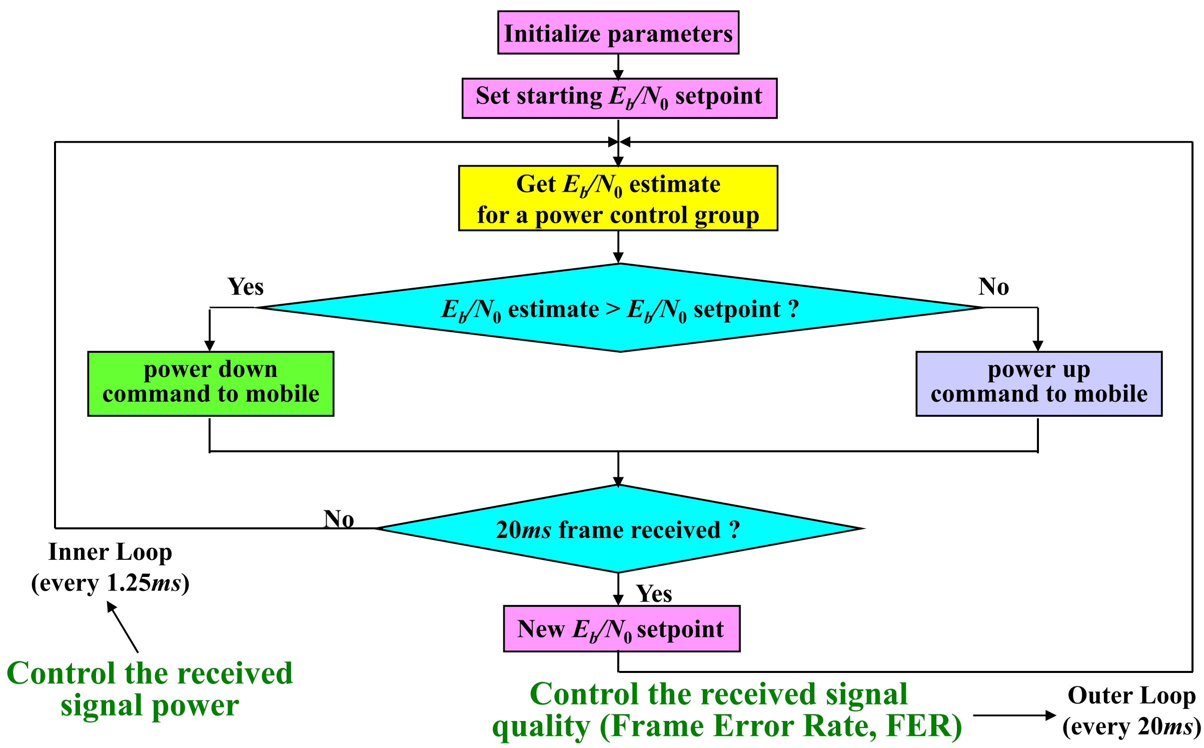
  $\Rightarrow$ The MS should decreases (or increases) the transmission power

Power Control Mechanism – Close-loop

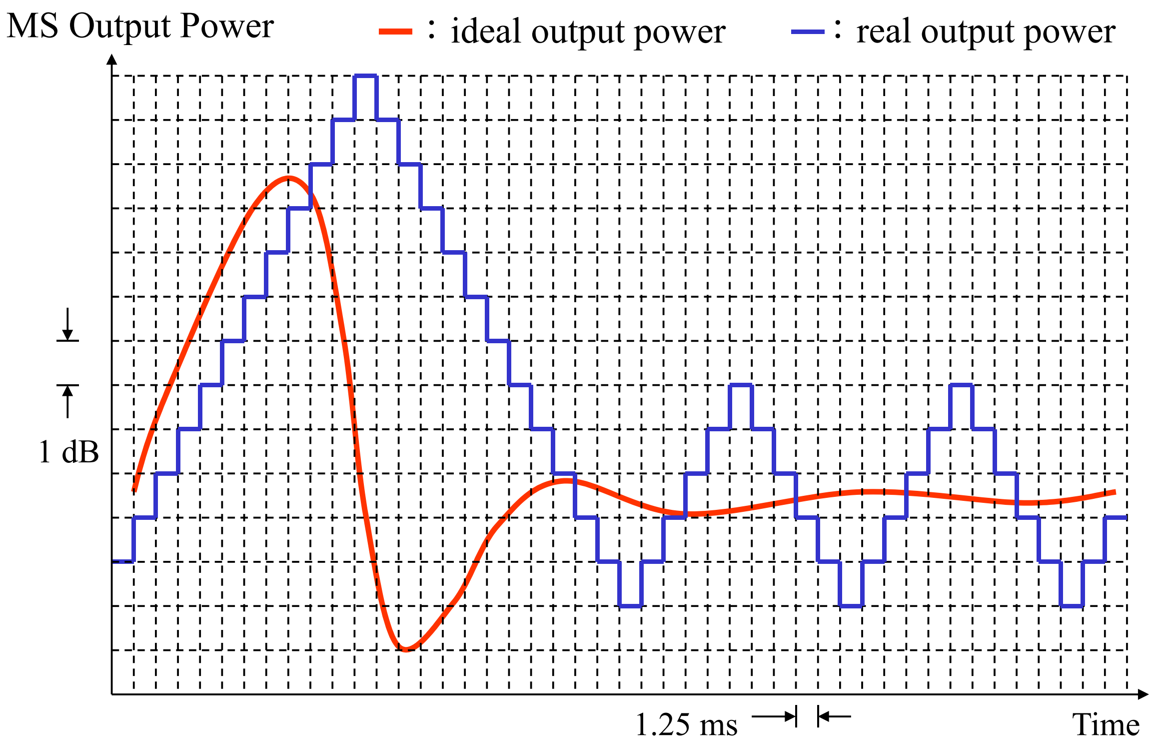
- Close-loop power control:
  - Executed by the MS in collaboration with the serving BS
  - Adjust the average transmission power to compensate the variation due to **small-scale fading (fast fading)**
  - Provide a fast power control mechanism with **a small dynamic range** per step
- The serving BS receive the signal power from an MS
- When the **received signal power** (or CIR) is below (above) a specific threshold

  ⇒ The BS sends a power control message which directs the MS to increase (or to decrease) the transmission power
- The MS executes the power control command

Reverse Link Close Loop Power Control



Power Control Level



System Capacity

Capacity of CDMA Systems – Up-link

- Assuming **perfect up-link** power control
  - d is the required E_b/N_t
  - g is the processing gain
  - S is the received signal strength
  - F is the base station noise figure
  - N_0 is the spectral density of thermal noise
  - W is the system bandwidth
  - α is the voice activity factor
  - β is the interference factor
  - N is the average number of users in a cell

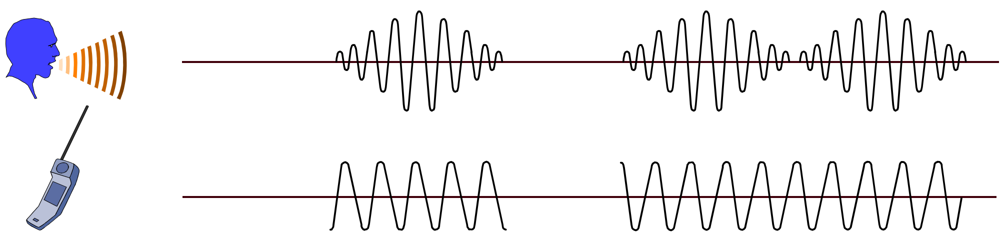
The factor corresponds to the interference coming from all neighboring cells

$$d = \frac{gS}{\underbrace{FN_0W}_{\text{Thermal Noise}} + \underbrace{\alpha(1+\beta)(N-1)S}_{\text{Co-channel Interference}}}$$

Voice Activity Factor and CDMA Capacity

- α: the **voice activity factor**
  - If the voice does not activate, there is no need to transmit the radio signal
  - For a two-way conversation, the voice activity factor is about **35% ~ 40%**
- The average interfering users in a cell is

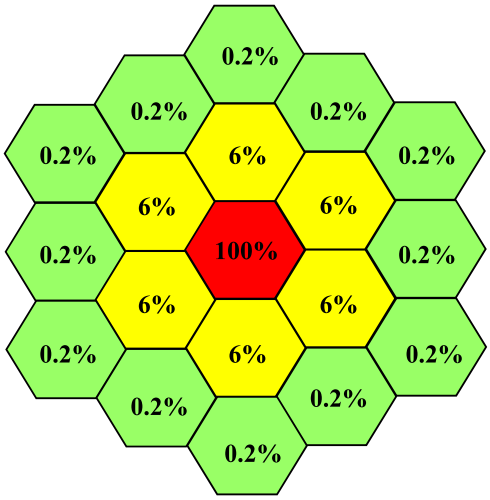
$$\alpha(N-1)$$



Capacity of CDMA Systems – Up-link (Cont.)

- β: the **interference factor**
  - $\alpha(N-1)S$ is the co-channel interference (CCI) coming from the serving cell
  - The normalized co-channel interference coming from all neighboring cells is

$$\beta = 6\times 6\% + 12\times 0.2\% + \cdots \approx 40\%$$



  - The total CCI is

$$\alpha(1+\beta)(N-1)S$$

Capacity of CDMA Systems – Up-link (Cont.)

- Solve N to obtain the average system capacity

$$N = \frac{g}{\alpha d(1+\beta)} + 1 - \frac{FN_0W}{\alpha(1+\beta)S}$$

- The **pole point** is obtained by letting the signal-to-noise ratio go to **infinity** (i.e., $S \to \infty$)

$$N_{\max} = \frac{g}{\alpha d(1+\beta)} + 1$$

- The **pole capacity** is the maximum system capacity in a cell
  - Is achievable only in theory
  - The number of users that can be put on an actual system is typically smaller than the pole capacity
    - Typically **50% to 60%**

Example: Capacity of cdma2000 Systems

- For **cdma2000** systems up-link

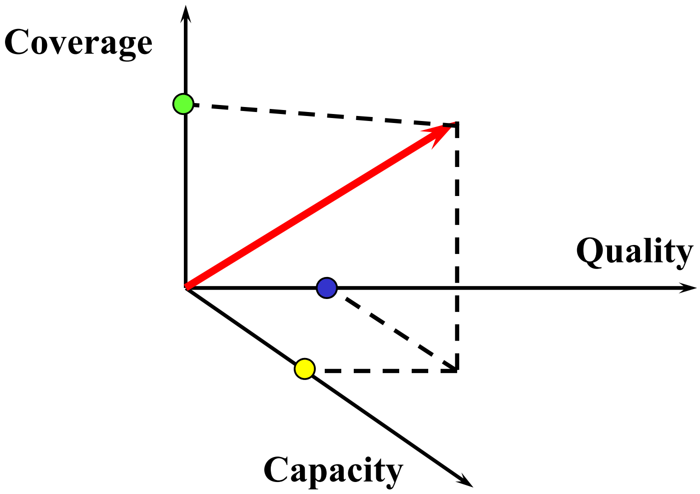
Parameter	8 kb vocoder	13 kb vocoder
W	1.23 MHz	1.23 MHz
R	9.6 kbps	14.4 kbps
$G = W / R$	128	85
α	0.4	0.4
β (for 3 sector)	0.85	0.85
D	5.01 (7 dB)	5.01 (7 dB)
N_{max}	35	24
Capacity Loading	57%	57%
No. of CEs per Sector	**20**	**13**
Offered Erlangs at 2% Blocking	13.2	7.4

Capacity of CDMA Systems – Down-link

- For **down-link**, the system capacity is hard to determinate and strongly depends on
  - The distribution of mobile users
  - The available transmission power
  - The available code channels

Capacity, Quality and Coverage of CDMA

- For CDMA systems, the **system capacity**, the **signal quality** and the **cell coverage** are strongly correlated
  - **Radio resource** (bandwidth and power) is fixed



Capacity Limitation of CDMA

- The capacity limitation for CDMA systems is due to many different reasons (Bandwidth is assumed to be fixed)
- In **down-Link**, all channels are coming from the same transmitter
  - **Power resource** limitation (available power is limited)
  - **Code resource** limitation (available orthogonal codes are limited)
- In **up-Link**, different channels are coming from different terminals
  - **Co-channel interference** is the major limitation (an acceptable CIR is desired)
- **Hardware** limitation: the number of channel elements (CE) is the nature limitation of the system capacity

RAKE Receiver

Diversity Techniques

- There are many diversity techniques have been applied in wireless communications, including
  - Space diversity
  - Angle diversity
  - Polarization diversity
  - Frequency diversity
  - Time diversity
  - Multipath diversity
- **Multipath diversity**:
  - No extra antennas and/or frequency resource are required
  - Resolve multipath components at different delays
  - Use DSSS signaling along with a **RAKE receiver**

Multipath Signals

- For narrow-band systems, **channel equalization** is generally used to eliminate the **inter-symbol interference** (ISI)
- Due to the wideband nature of CDMA systems, more paths (one in each chip) can be resolved, and the traditional equalization is no longer an option
- The receiver needs to **resolve** all the paths and then **combines** them
  - RAKE receiver combines the signals from all paths to produce one clear signal
  - Individual paths are found **(synchronized to)** by cross-correlating a reference pattern with the received signal

RAKE Receiver

- Suppose that desired signal is transmitted over a multipath channel
  - The received signal is

$$S_r(t) = \sum_i A_i S(t - \tau_i) \exp(j\phi_i)$$

  - A_i is the **channel gain** corresponds to the i-th path
  - τ_i is the **time delay** corresponds to the i-th path
- After passing through the filter matched to the signal $S(t)$
  - The resultant signal at the filter output is

$$S_{rf}(t) = \sum_i A_i R(t - \tau_i - T) \exp(j\phi_i)$$

  - $R(\tau)$ is the **auto-correlation function** of the transmitted signal

RAKE Receiver (Cont.)

- In a RAKE receiver, one **RAKE finger** is assigned to each multipath
  - Maximizing the amount of received signal energy
  - The number of fingers is limited
- Each of these different paths are combined to form a composite signal that is expected to have substantially better characteristics than a single path
- For **maximum ratio combining (MRC)**, the RAKE receiver needs the knowledge of channel parameters
  - Number of paths
  - Path delays
  - Channel gains (complex-valued)

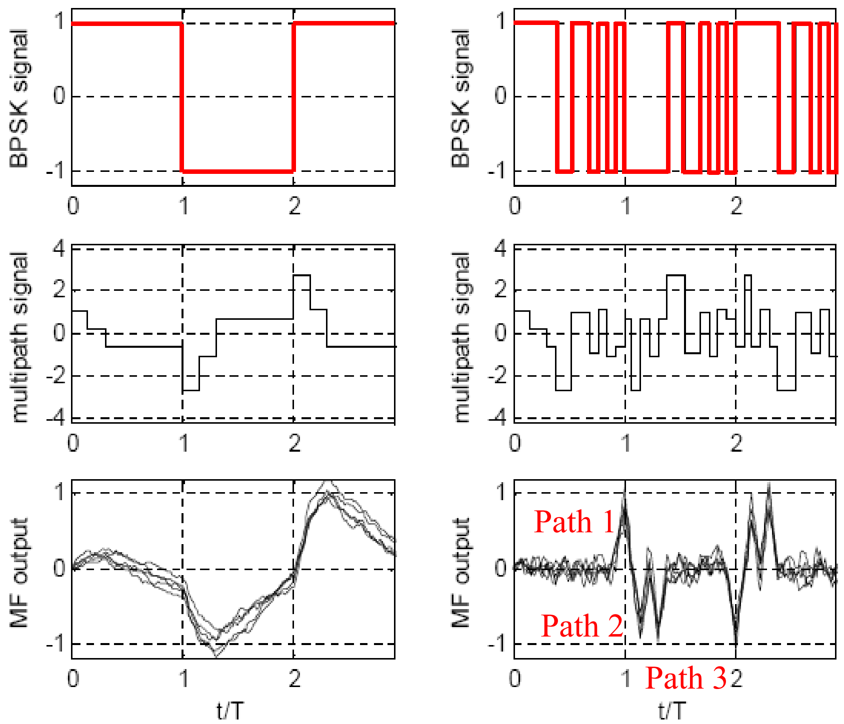
CDMA Receiver (Cont.)

- In a CDMA receiver the following steps take place
  - Two-level spreading: Long code (user) and Short code (BS)
- **Descrambling**: Received signals are multiplied by the scrambling code and delayed versions of the scrambling code
  - The **delays** are determined by a **path searcher** prior to descrambling
- **Despreading**: The descrambled data of each path are despread by simply multiplying the descrambled data by the spreading code
- **Integration and dump**: The despread data is then integrated over one symbol period
  - Give one complex sample output per QPSK symbol
  - This process is carried out for all the paths

CDMA Receiver (Cont.)

- **Combining**: The same symbols obtained via different paths are then combined together
  - Apply the corresponding channel information
  - Use a combining scheme like maximum ratio combing (MRC)
- **Decision**: The combined outputs are then sent to a decision device
  - To decide on the transmitted bits
- The **path searcher** identifies the location (in chips), i.e., the path delay, for each independent strong path that are present in the received signal
  - This is done mainly by correlating the received **pilot signal** (with its unique scrambling code) with the stored scrambling code

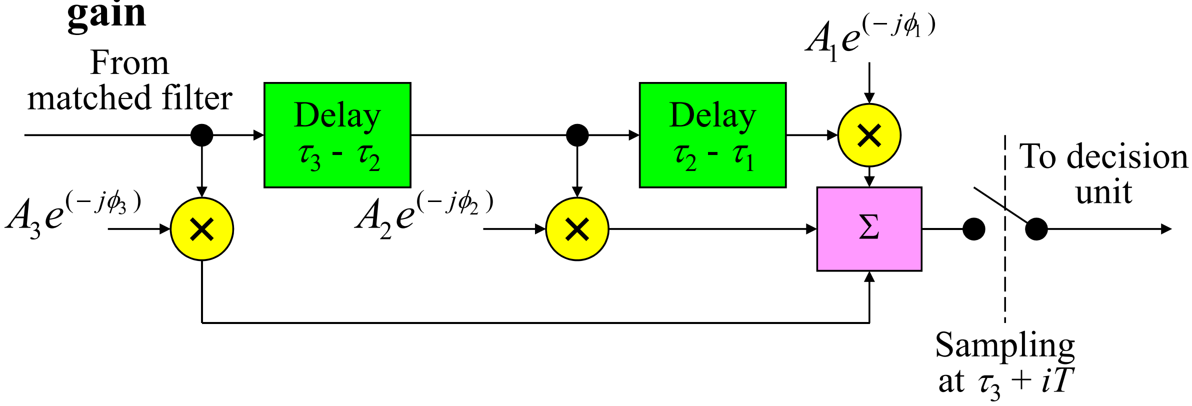
Received Signals after Correlator



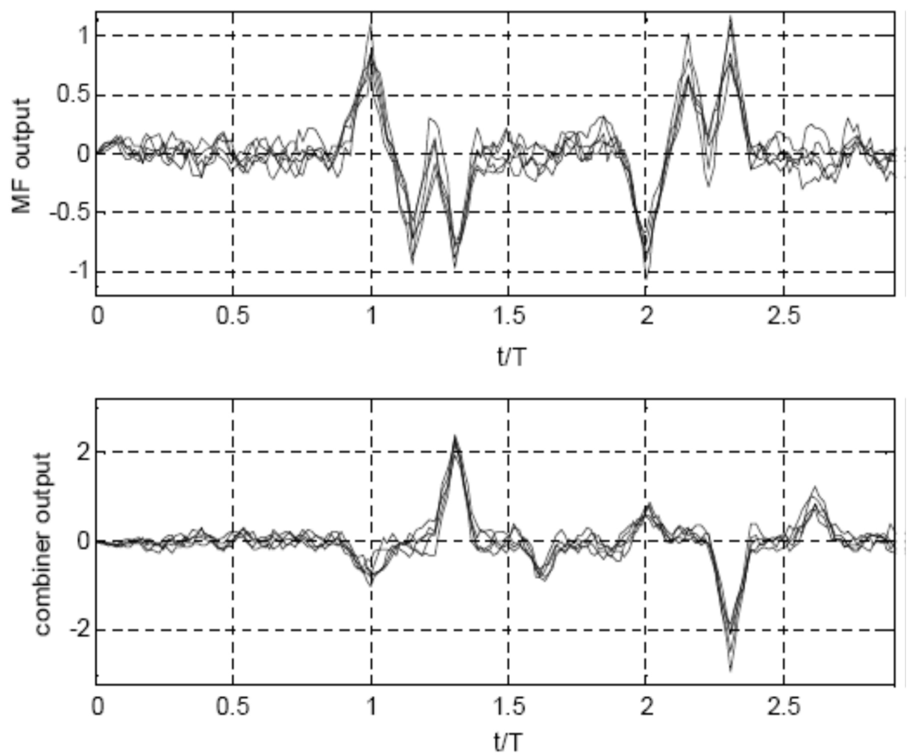
BPSK signal **DSSS signal**

Maximum Ratio Combining

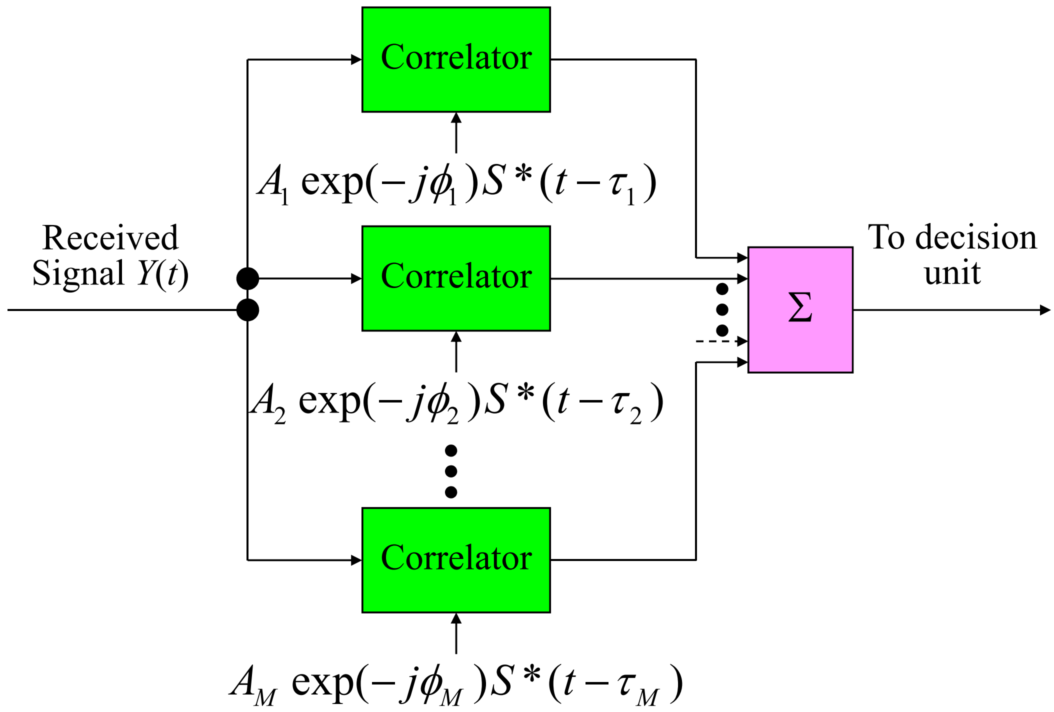
- **Path synchronization**:
  - All paths are synchronized to **the last arriving path**
  - The first path is delayed by τ_3 - τ_1
  - The second path is delayed by τ_3 - τ_2
- Each path is weighted by the corresponding estimated **channel gain**



Combiner Output

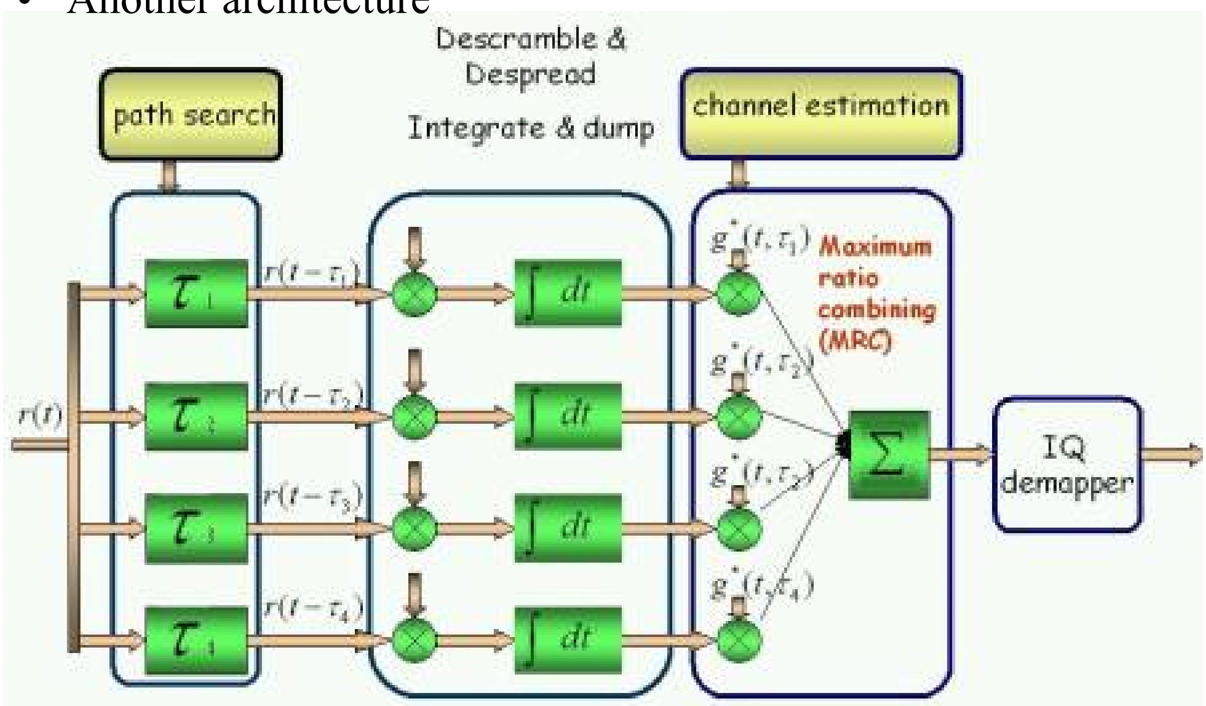


Correlator-based RAKE Receiver



RAKE Receiver (Cont.)

- Another architecture



3G CDMA Systems

Second Generation CDMA System

- The first digital cellular system based on CDMA was standardized as Interim Standard 95 **(IS-95)**
  - By US Telecommunication Industry Association **(TIA)** (1993)
  - This is one of the **2G** mobile cellular systems
- The International Telecommunication Union **(ITU)** formulated a plan to implement a global frequency band in the **2GHz** band
  - Support the **worldwide** wireless communication standard called International Mobile Telecommunication 2000 **(IMT-2000)**
  - The **3G** mobile cellular systems
  - Originally planned to provide service in year 2000

IS-95 System Parameters (I)

Parameter	Downlink	Uplink
Frequency band	869–894 MHz	824–849 MHz
Carrier spacing	1.25 MHz	1.25 MHz
Chip rate	1.2288 Mchips/s	1.2288 Mchips/s
Speech coder	CELP 8kbps 13 kbps EVRC 8kbps	CELP 8kbps 13 kbps EVRC 8kbps
Data rates	9.6 kbps set, 14.4 kbps set	9.6 kbps set, 14.4 kbps set
Power control frequency	Slow power control (Frame based)	800 Hz (800 bps)
Scrambling	QPSK spreading (Short code, period = 2^{15}) Orthogonal spreading (64 Hadamard codes)	QPSK spreading (Short code, period = 2^{15})

IS-95 System Parameters (II)

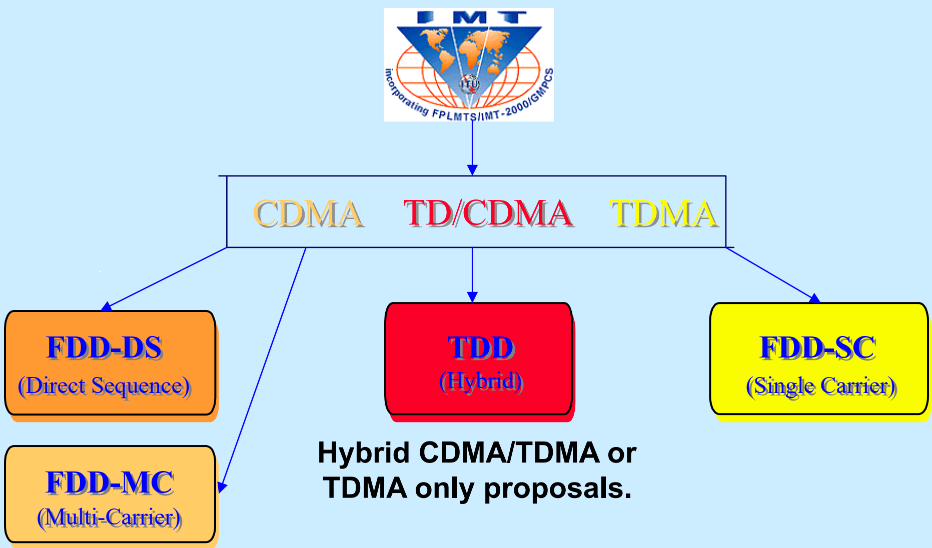
Parameter	Downlink	Uplink
DS spreading	Binary spreading Long code, period = $2^{42} - 1$	Binary spreading Long code, period = $2^{42} - 1$
FEC code	Convolutional code, (Rate 1/2, constraint lenth = 9)	Convolutional code, (Rate 1/2 or 1/3, constraint lenth = 9) Orthogonal modulation
Frame duration	20 ms	20 ms
Interleaving	Block interleaver, duration = 20 ms	Block interleaver, duration = 20 ms
Receiver	Coherent demodulation (Pilot signal) Rake receiver	Noncoherent demodulation Rake receiver

Third Generation CDMA Systems

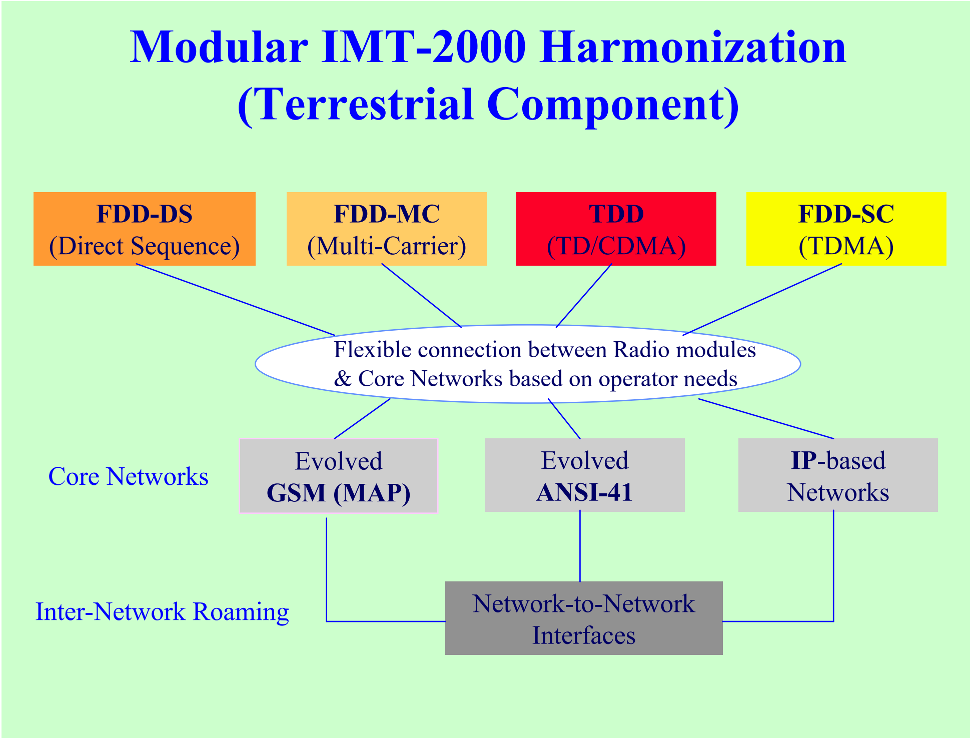
- ITU determined new spectrum bands to accommodate the 3G mobile cellular systems
  - 806–960 MHz, 1710–1885 MHz, and 2500–2690 MHz
- Initially, ITU planned to harmonize a **single** wireless communication standard, but it splits into two communities
  - **3GPP** (3G Partnership Project): it proposes the **WCDMA** (Wideband CDMA) standard based on the network fundamentals of **GSM**
  - **3GPP2**: it proposes the **cdma2000** standard evolved from the IS-95 standard
  - Both base on the **CDMA** transmission technology

IMT-2000 RTT Standards

IMT-2000 Terrestrial Radio Standards

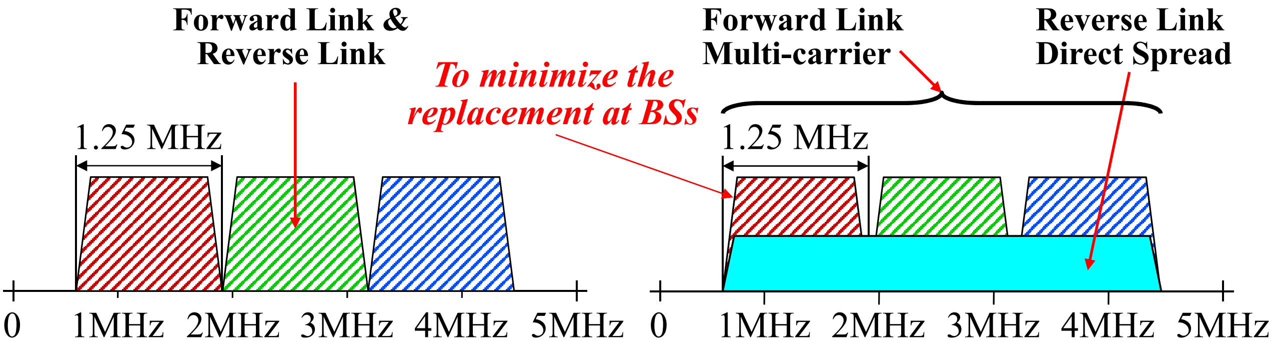


IMT-2000 Harmonization



cdma2000 Carriers

- To provide high-rate transmission and backward compatibility with IS-95, cdma2000 supports SR (Spreading Rate) 1 and SR 3 modes
  - SR 1: the conventional IS-95 system (bandwidth 1.25 MHz)
  - SR 3: the **MC (Multi-Carrier)** mode with three times bandwidth (claimed to be 5 MHz)



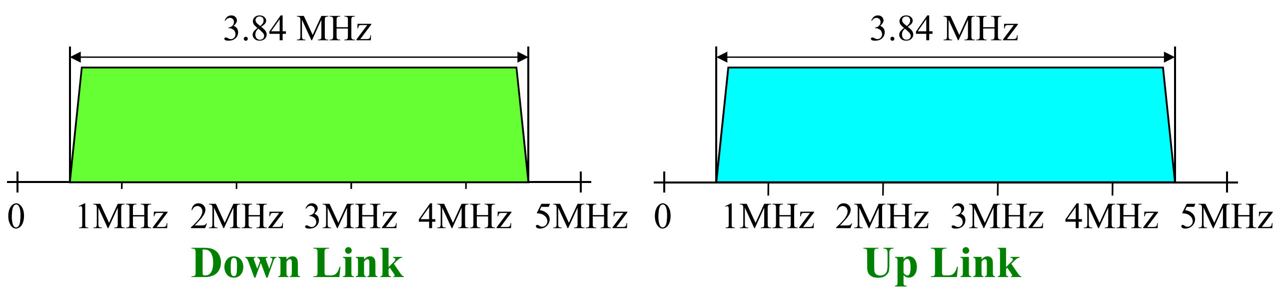
3G-1X (SR 1) **3G-3X (SR 3)**

cdma2000 System Key Parameters

- The chip rate of cdma2000 systems is
  - SR 1: FL/RL **1.2288 Mcps**
  - SR 3: FL **1.2288 Mcps** ×3; RL **3.6864 Mchips/s**
- Support of IMT-2000 data rates:
  - Vehicular - **144 kbps** (supported by 1X systems)
  - Pedestrian - **384 kbps** (supported by 3X systems)
  - Indoor - **2 Mbps** (supported by 3X systems)
- The processing gain is
  - 144 kbps: 8
  - 384 kbps: 8 (supported by 3X systems)
  - 2 Mbps: 4 (supported by 3X systems with 2 code channels)

W-CDMA Carrier

- WCDMA is a new system without the issue of backward compatibility
- Only DS (Direct Spreading) mode is supported
  - It is not MC (Multi-Carrier) mode
  - It supports only one spreading rate – **3.84 Mchips/s** (with the bandwidth claimed to be 5 MHz)



WCDMA System Key Parameters

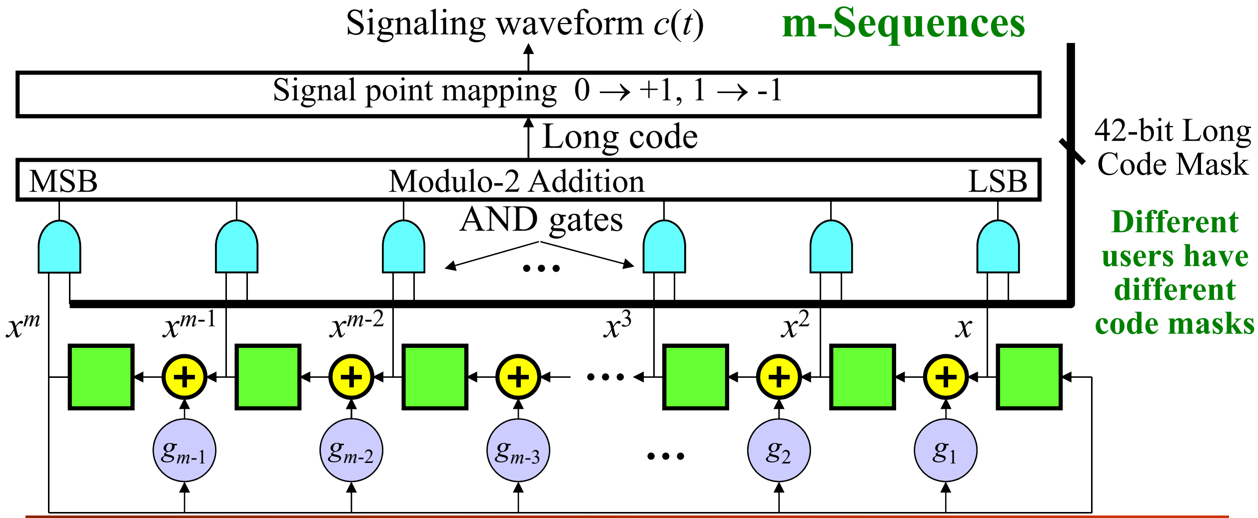
- The chip rate of WCDMA systems is
  - FL/RL **3.84 Mchips/s**
- Support of IMT-2000 data rates:
  - Vehicular - **144 kbps** (supported by 1X systems)
  - Pedestrian - **384 kbps** (supported by 3X systems)
  - Indoor - **2 Mbps** (supported by 3X systems)
- The processing gain is
  - 144 kbps: 26
  - 384 kbps: 10
  - 2 Mbps: 4 (supported by 2 code channels)

cdma2000 vs WCDMA

- Chip rate:
  - cdma2000: 1.2288/3.6864 Mcps
  - W-CDMA: 3.84 Mcps
- Pilot:
  - cdma2000: A BS transmits a common pilot for all users
  - W-CDMA: A BS transmits individual pilot to each user
- Synchronization:
  - cdma2000: BSs must be synchronous (GPS receiver is required)
  - W-CDMA: BSs do not need to be synchronous (Asynchronous)

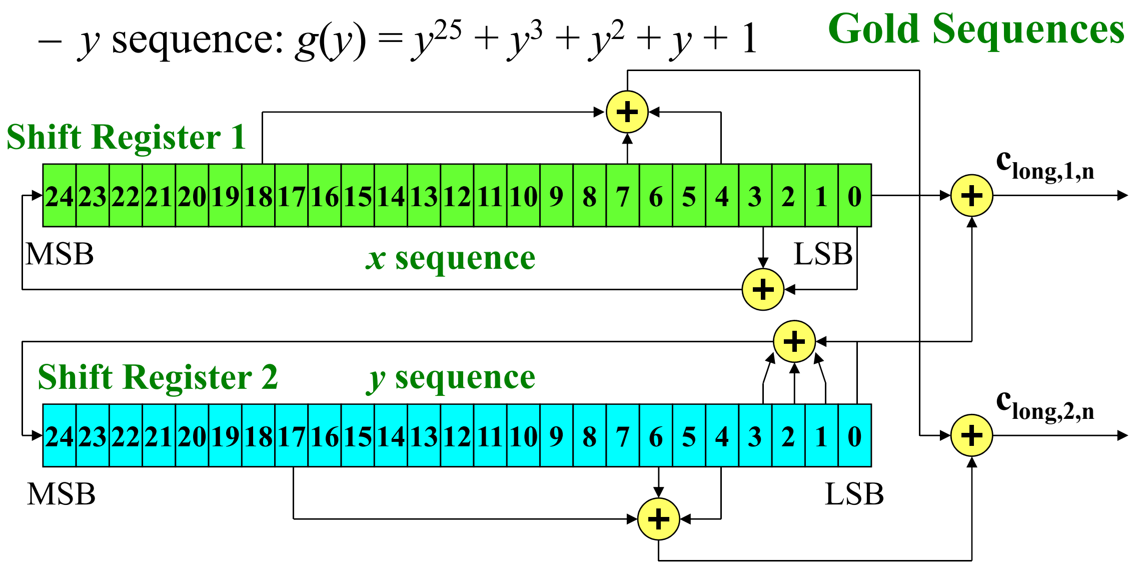
cdma 2000 Long Code Generator

- The generating polynomial for the long code sequence used in cdma 2000 systems is
  - $g(x) = x^{42} + x^{35} + x^{33} + x^{31} + x^{27} + x^{26} + x^{25} + x^{22} + x^{21} + x^{19} + x^{18} + x^{17} + x^{16} + x^{10} + x^{7} + x^{6} + x^{5} + x^{3} + x^{2} + x^{1} + 1$



WCDMA Uplink Long Scrambling Sequence

- In the uplink of WCDMA systems, two long scrambling sequences $c_{long,1,n}$ and $c_{long,2,n}$ are constructed
  - x sequence: $g(x) = x^{25} + x^{3} + 1$
  - y sequence: $g(y) = y^{25} + y^{3} + y^{2} + y + 1$



WCDMA Downlink Long Scrambling Sequence

- In the downlink of WCDMA systems, two long scrambling sequences $c_{long,1,n}$ and $c_{long,2,n}$ are constructed
  - x sequence: $g(x) = x^{18} + x^7 + 1$
  - y sequence: $g(y) = y^{18} + y^{10} + y^7 + y^5 + 1$