EC744 Wireless Communications Spring 2007

Mohamed Essam Khedr

Department of Electronics and Communications

Spread spectrum, CDMA, OVSF, MC-CDMA

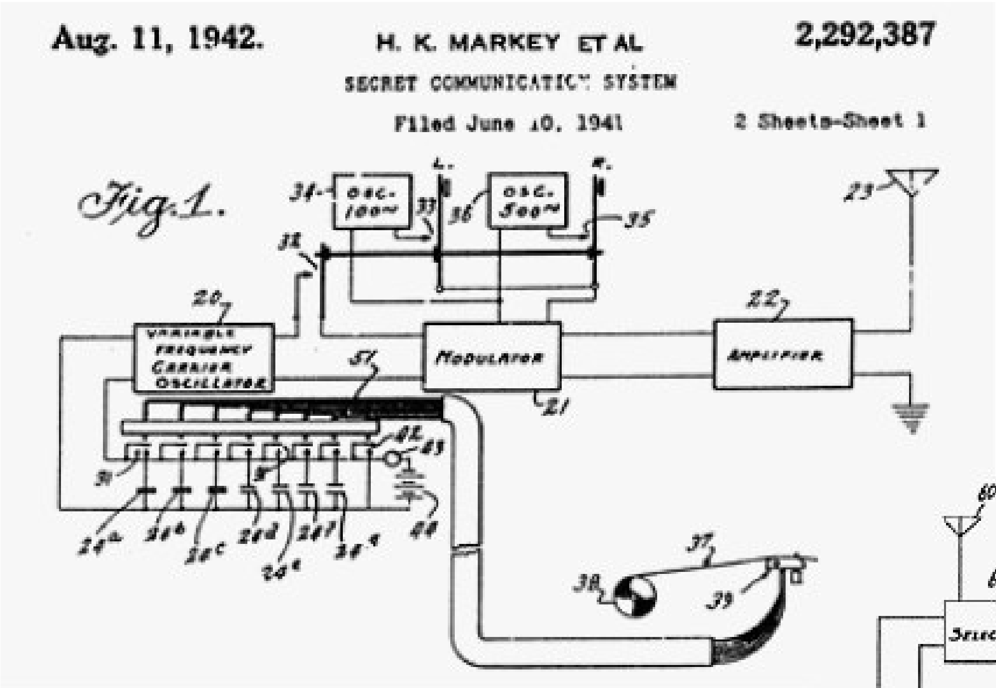
Spread Spectrum Communications - Agenda

- Basic principles and block diagrams of spread spectrum communication systems
- Characterizing concepts
- Types of SS modulation: principles and circuits
  - direct sequence (DS)
  - frequency hopping (FH)
- Error rates
- Spreading code sequences; generation and properties
  - Maximal Length (a linear, cyclic code)
  - Gold
  - Walsh
- Orthogonal Variable spreading factor
- Multicarrier CDMA

Historical Background: Hedy Lamar

- Hedy Lamarr (Hedwig Kiesler) and George Antheil had developed a system in August 1942 that was called Frequency Hopping
- Idea was to build up a remote controlled torpedo and the work results in a patent called Secret Communication System. But American military was not interested until 1963 (Kuba).
- Lamar was born 1913 in Austria and worked as an actress in Hollywood
- Antheil was born in Paris and had a piano bar.

Hedy Lamarr (November 9, 1913 – January 19, 2000) was an Austrian/American actress and communications technology innovator. Though known primarily for her great beauty, she also co-invented the first form of spread spectrum, a key to modern wireless communication


Aug. 11, 1942.
H. K. MARKEY ET AL
2,292,387
SECRET COMMUNICATION SYSTEM
Filed June 10, 1941
2 Sheets-Sheet 1
Fig.1.
OSC. 100~
OSC. 500~
VARIABLE FREQUENCY CARRIER OSCILLATOR
MODULATOR
AMPLIFIER

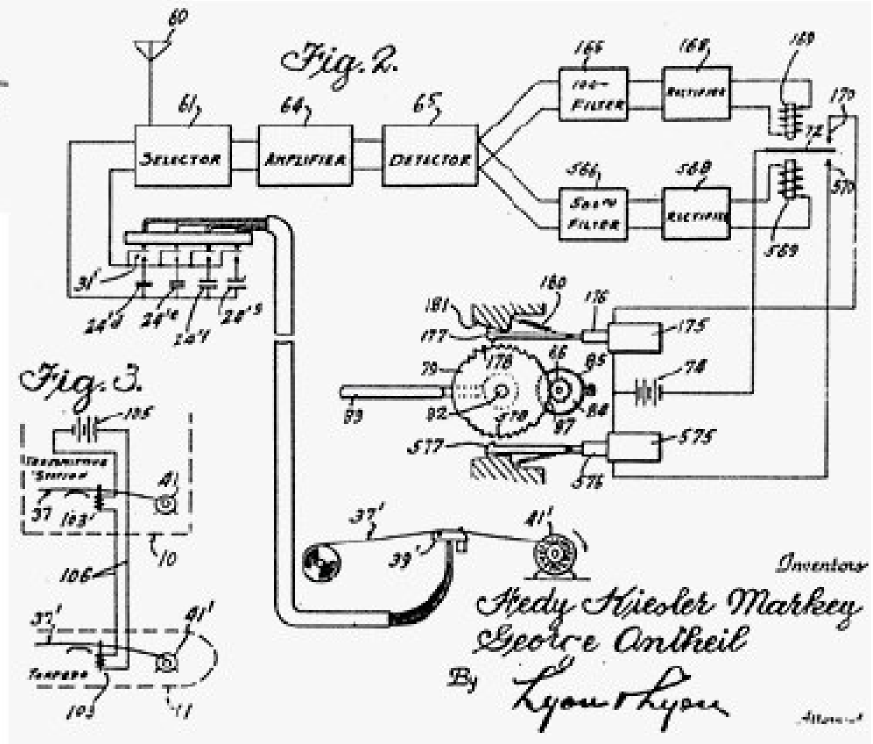
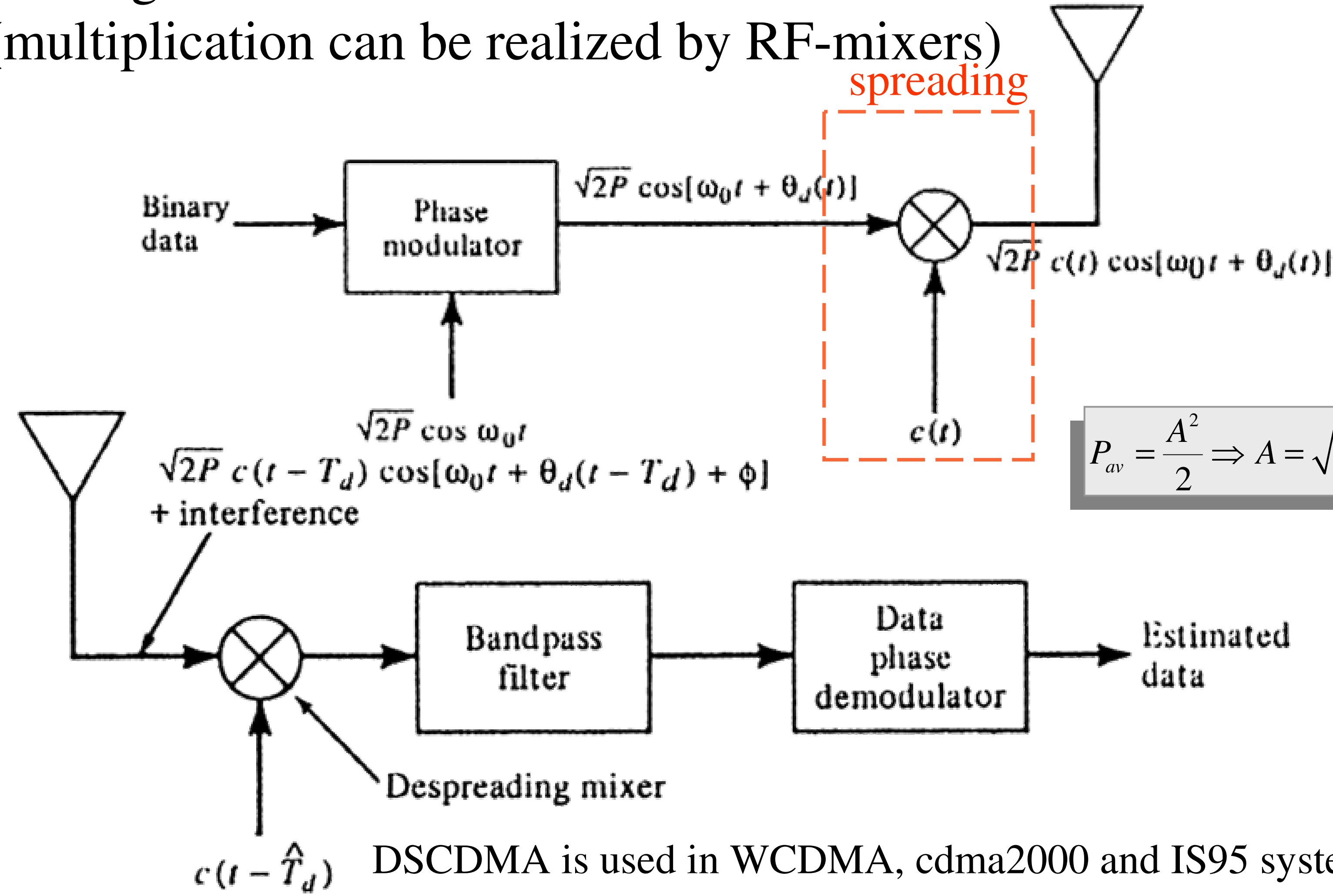


Fig.2.
SELECTOR
AMPLIFIER
DETECTOR
100~ FILTER
500~ FILTER
RECTIFIER
Fig.3.
Inventors
Hedy Kiesler Markey
George Antheil
By

Direct Sequence Spread Spectrum (DS-SS)

- This figure shows BPSK-DS transmitter and receiver (multiplication can be realized by RF-mixers)

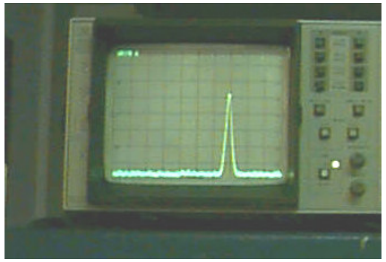


$$P_{av} = \frac{A^2}{2} \Rightarrow A = \sqrt{2P_{av}}$$

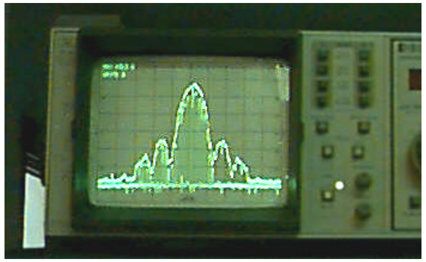
DSCDMA is used in WCDMA, cdma2000 and IS95 systems

Characteristics of Spread Spectrum

- Bandwidth of the transmitted signal *W* is much greater than the original message bandwidth (or the signaling rate *R*)
- Transmission bandwidth is independent of the message. Applied code is known both to the transmitter and receiver



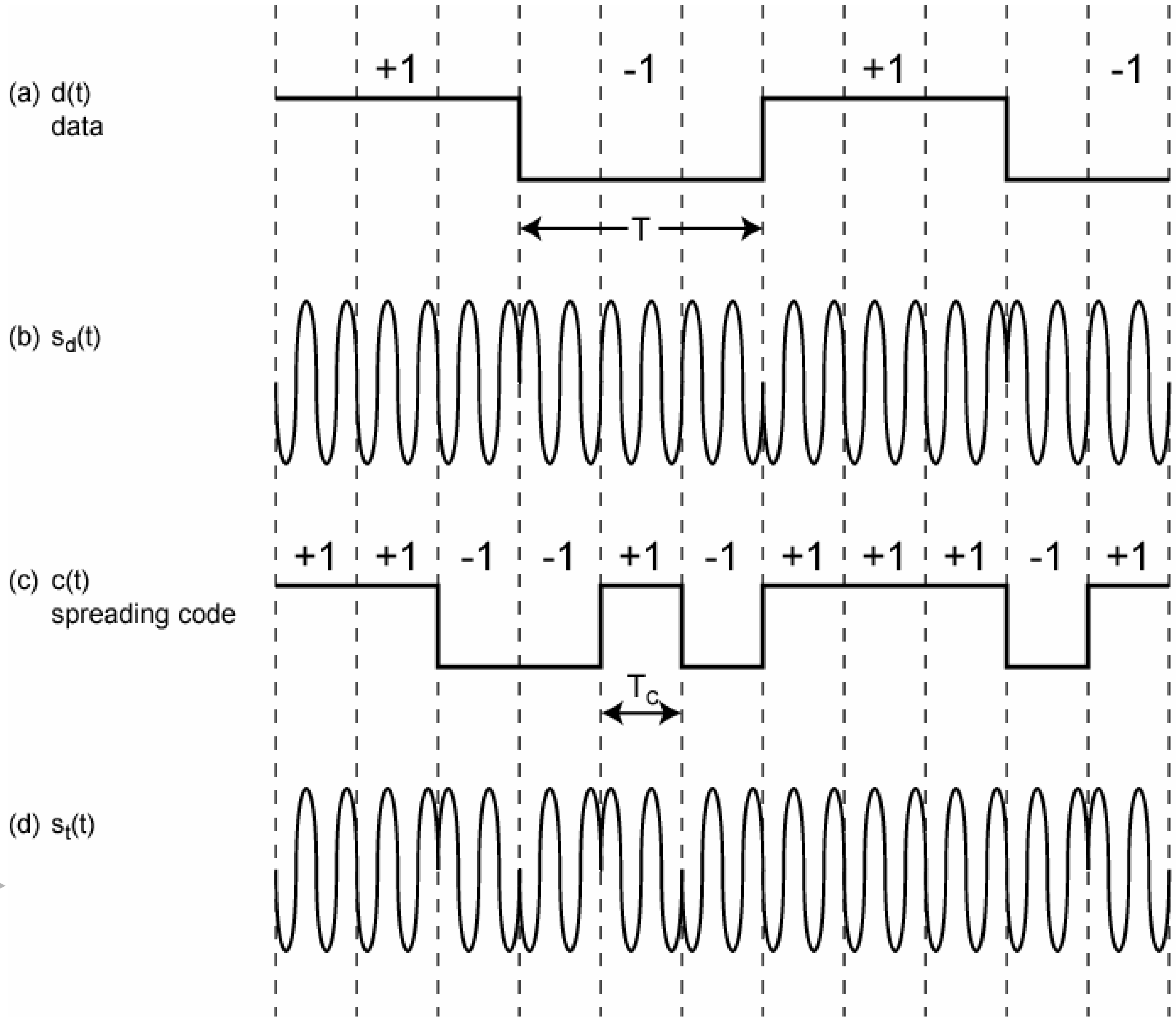
Narrow band signal (data)



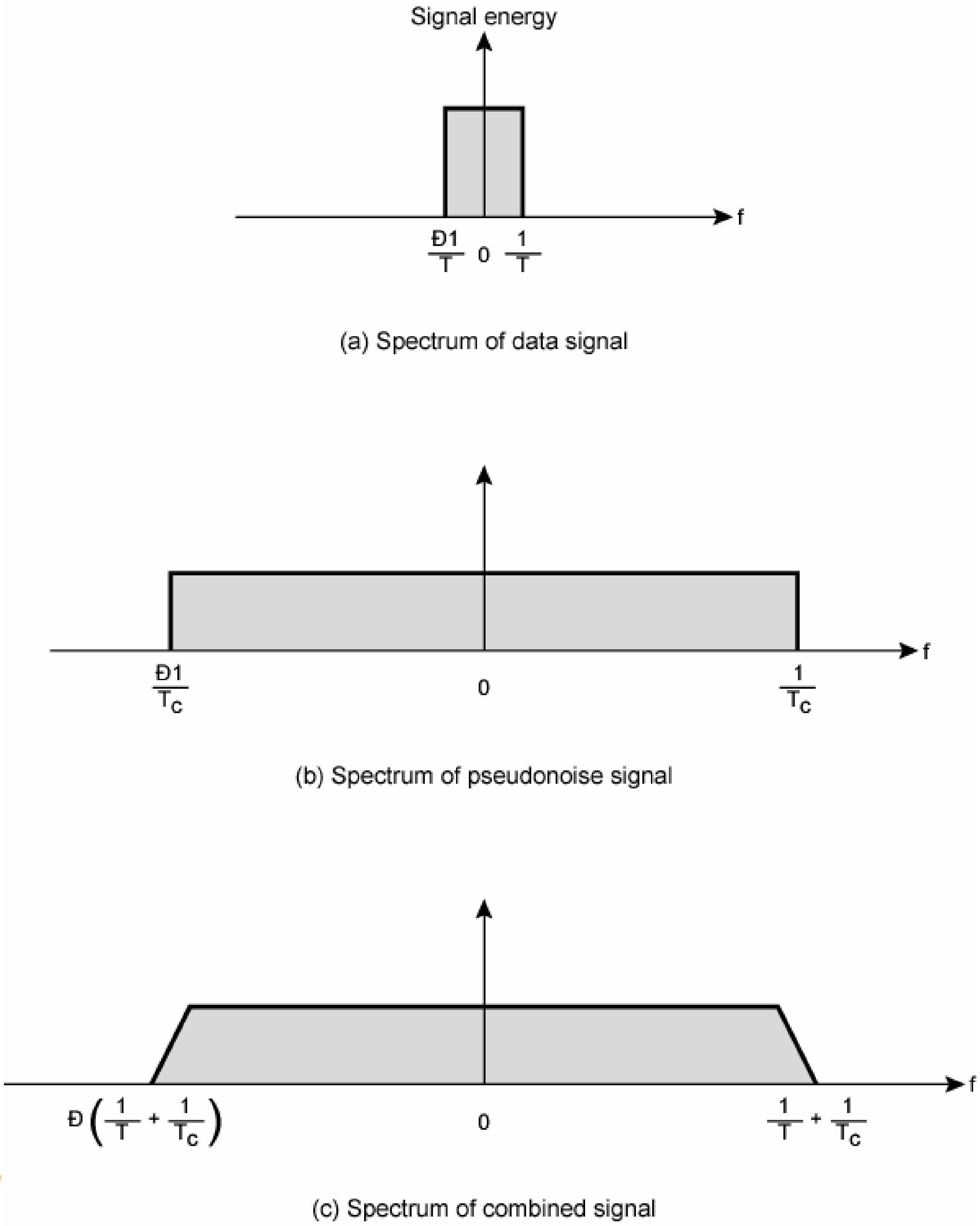
Wideband signal (transmitted SS signal)

- Interference and noise immunity of SS system is larger, the larger the processing gain $L_c = W / R = T_b / T_c$
- Multiple SS systems can co-exist in the same band (=CDMA). Increased user independence (decreased interference) for (1) higher processing gain and higher (2) code orthogonality
- Spreading sequence can be very long -> enables low transmitted PSD-> low probability of interception (especially in military communications)

Direct Sequence Spread Spectrum Using BPSK Example



Approximate Spectrum of DSSS Signal



Characteristics of Spread Spectrum (cont.)

- Processing gain, in general

$$L_c = W/R = (1/T_c)/(1/T_b) = T_b/T_c, L_{c,dB} = 10\log_{10}(L_c)$$

  - Large L_c improves noise immunity, but requires a larger transmission bandwidth
  - Note that DS-spread spectrum is a repetition FEC-coded systems

- Jamming margin

$$M_J = L_c - [L_{sys} + (SNR)_{desp}]$$

  - Tells the magnitude of additional interference and noise that can be injected to the channel without hazarding system operation.

Example:

$$L_c = 30\,\text{dB}, \text{available processing gain}$$

$$L_{sys} = 2\,\text{dB}, \text{margin for system losses}$$

$$SNR_{desp} = 10\,\text{dB}, \text{required SNR after despreading (at the RX)}$$

$$\Rightarrow M_j = 18\,\text{dB}, \text{additional interference and noise can deteriorate received SNR by this amount}$$

Characteristics of Spread Spectrum (cont.)

- Spectral efficiency E_{eff}: Describes how compactly TX signal fits into the transmission band. For instance for BPSK with some pre-filtering:

$$E_{eff} = R_b / B_T = R_b / B_{RF} \qquad L_c = T_b / T_c \Rightarrow L_c / T_b = 1 / T_c$$

$$B_{RF} \approx \frac{B_{RF,filt}}{k} \approx \frac{1/T_c}{\log_2 M} = \frac{L_c}{T_b \log_2 M}$$

$$\begin{cases} B_{RF,filt}: \text{bandwidth for polar mod.} \\ M: \text{number of levels} \\ k: \text{number of bits} \end{cases}$$

$$\Rightarrow E_{eff} = \frac{R_b}{B_{RF}} \approx \frac{1}{\cancel{T_b}} \frac{\cancel{T_b} \log_2 M}{L_c} = \frac{\log_2 M}{L_c}$$

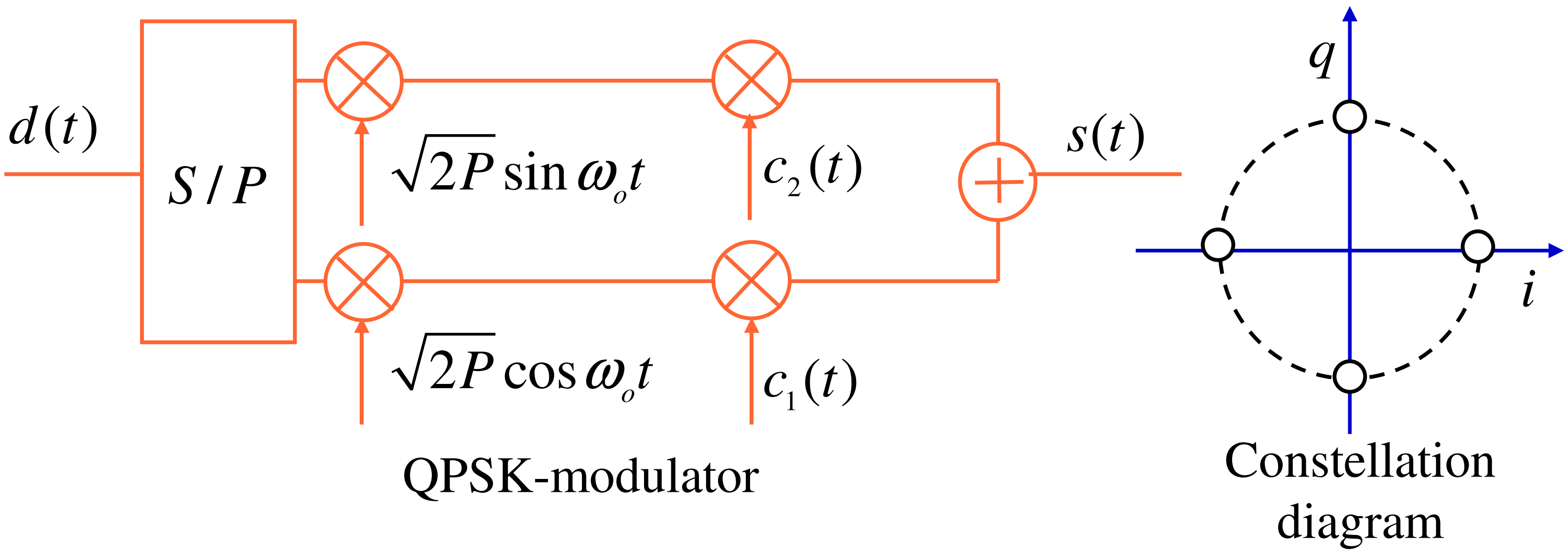
$$\left(M = 2^k \Rightarrow k = \log_2 M\right)$$

- Energy efficiency (reception sensitivity): The value of $\gamma_b = E_b / N_0$ to obtain a specified error rate (often 10^{-9}). For BPSK the error rate is

$$p_e = Q(\sqrt{2\gamma_b}), Q(k) = \frac{1}{\sqrt{2\pi}} \int_k^{\infty} \exp(-\lambda^2/2) d\lambda$$

- QPSK-modulation can fit twice the data rate of BPSK in the same bandwidth. Therefore it is more energy efficient than BPSK.

A QPSK-DS Modulator



- After serial-parallel conversion (S/P) data modulates the orthogonal carriers $\sqrt{2P}\cos(\omega_o t)$ and $\sqrt{2P}\sin(\omega_o t)$
- Modulation on orthogonal carriers spreaded by codes c_1 and c_2
- Spreading codes c_1 and c_2 may or may not be orthogonal (System performance is independent of their orthogonality, why?)
- What kind of circuit can make the demodulation (despreading)?

DS-CDMA (BPSK) Spectra (Tone Jamming)

- Assume DS - BPSK transmission, with a single tone jamming (jamming power *J [W]*). The received signal is

$$r(t)=\sqrt{2P}c_1(t-T_d)\cos\left(\omega_0 t+\theta_d(t)\right)+\sqrt{2J}\cos\left(\omega_0 t+\varphi'\right)$$

- The respective PSD of the received chip-rate signal is

$$S_r(f)=\frac{1}{2}PT_c\operatorname{sinc}^2\left[(f-f_0)T_c\right]+\frac{1}{2}PT_c\operatorname{sinc}^2\left[(f+f_0)T_c\right]$$
$$+\frac{1}{2}J\left\{\delta(f-f_0)+\delta(f+f_0)\right\}$$

Spreading of jammer power

- At the receiver *r(t)* is multiplied with the local code *c(t)* (=*despreading*)

$$d(t)=\sqrt{2P}c_1(t-T_d)c(t-\hat{T}_d)\cos\left(\omega_0 t+\theta_d(t)\right)$$
$$+\sqrt{2J}c(t-\hat{T}_d)\cos\left(\omega_0 t+\varphi'\right)$$

data

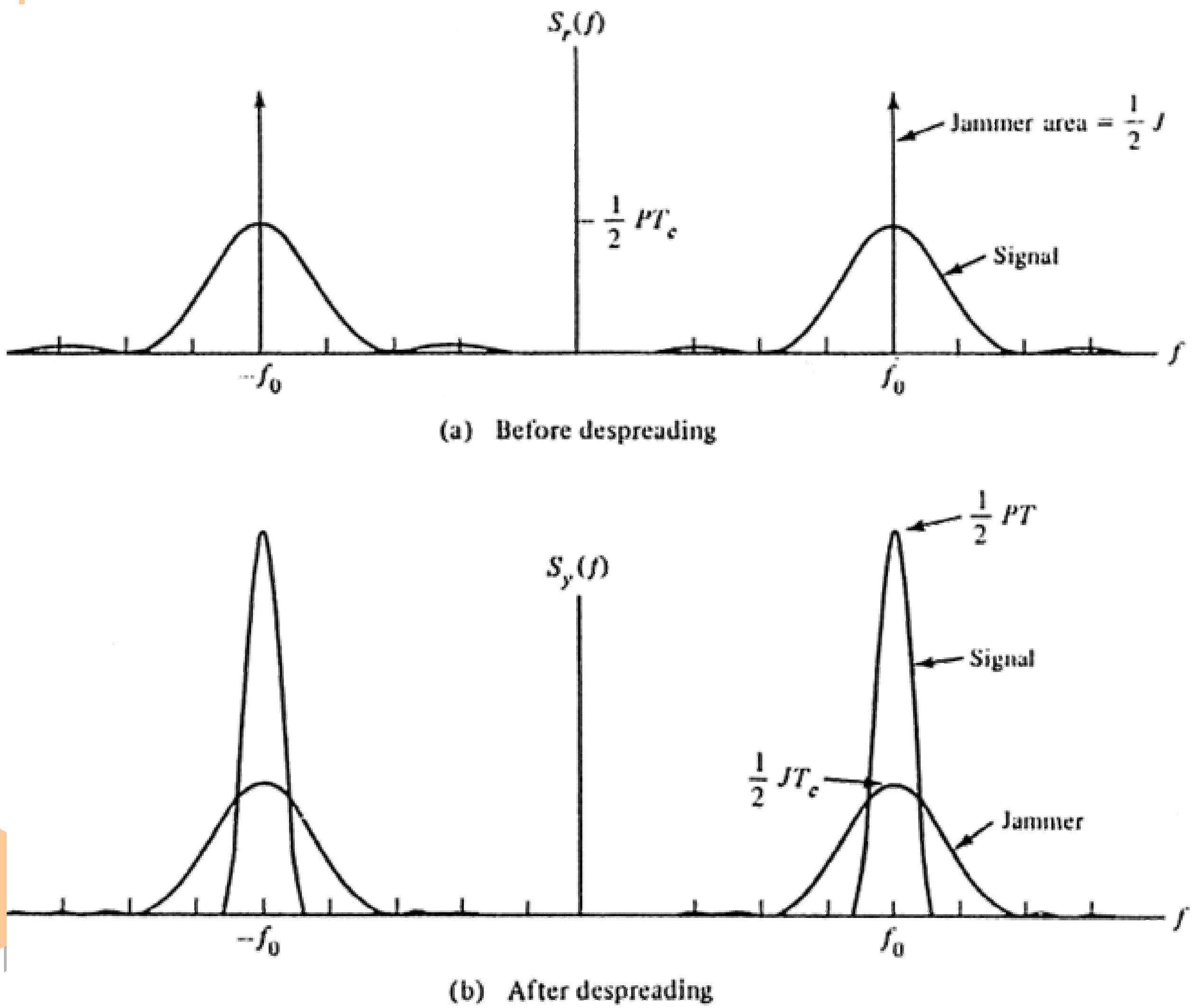
- The received signal and the local code are phase-aligned:

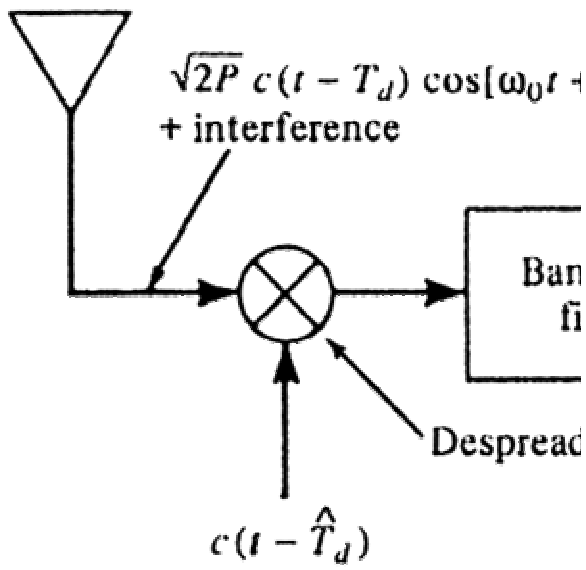
$$c_1(t-\hat{T}_d)c(t-T_d)=1\Rightarrow\; S_d(f)=\frac{1}{2}PT_b\operatorname{sinc}^2\left[(f-f_0)T_b\right]+\frac{1}{2}PT_b\operatorname{sinc}^2\left[(f+f_0)T_b\right]$$
$$+\underbrace{\frac{1}{2}JT_c\operatorname{sinc}^2\left[(f-f_0)T_c\right]+\frac{1}{2}JT_c\operatorname{sinc}^2\left[(f+f_0)T_c\right]}_{F\left\{\sqrt{2J}c(t-\hat{T}_d)\cos(\omega_0 t+\varphi')\right\}}$$

Data spectra after phase modulator

Tone Jamming (cont.)

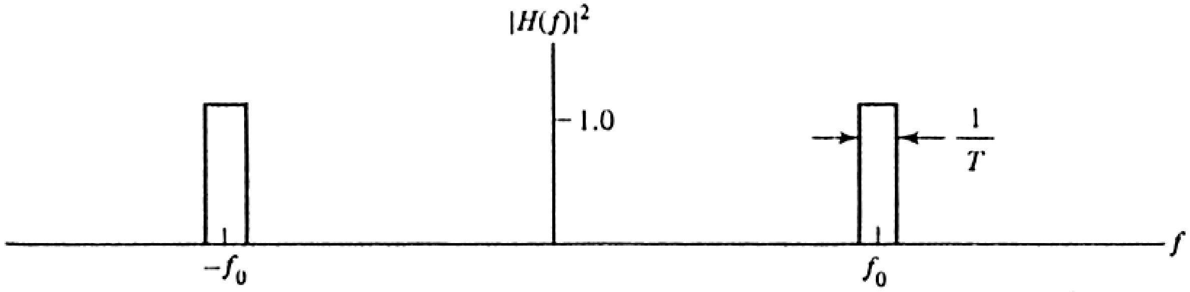
- Despreading spreads the jammer power and despreads the signal power:



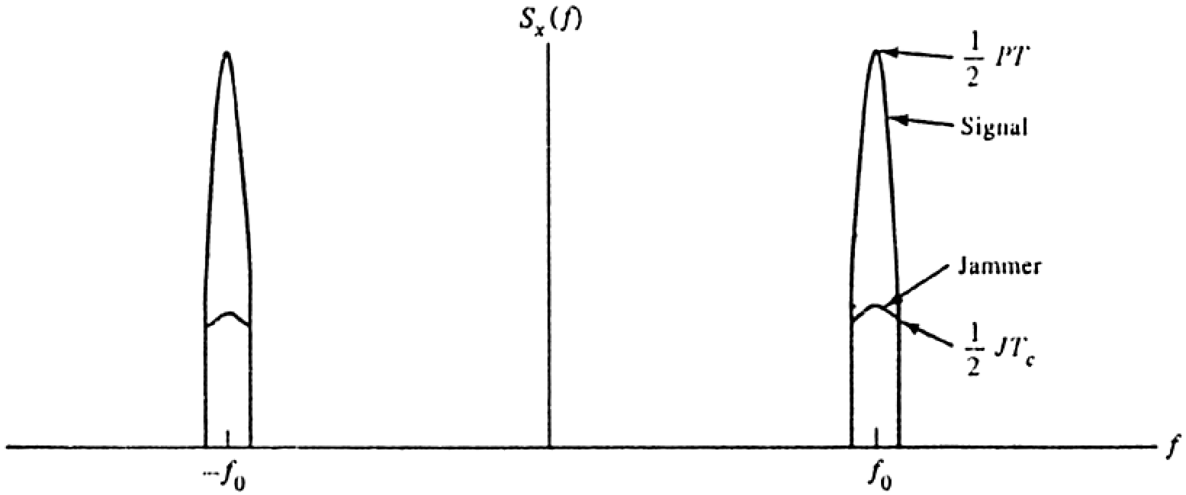


Tone Jamming (cont.)

- Filtering (at the BW of the phase modulator) after despreading suppresses the jammer power:



(c) IF filter power transfer function



(d) Output of IF filter

Error Rate of BPSK-DS System*

- DS system is a form of coding, therefore number chips, eg code weight determines, from its own part, error rate (code gain)
- Assuming that the chips are uncorrelated, prob. of code word error for a binary-block coded BPSK-DS system with code weight *w* is therefore

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0} R_c w_m}\right), R_c = k/n \ (= \text{code rate})$$

- This can be expressed in terms of processing gain L_c by denoting the average signal and noise power by P_{av}, N_{av} , respectively, yielding

$$E_b = P_{av} T_b, N_0 = N_{av} T_c \Rightarrow$$

$$P_e = Q\left(\sqrt{\frac{2P_{av}T_b}{N_{av}T_c} R_c w_m}\right) = Q\left(\sqrt{\frac{2P_{av}}{N_{av}} L_c R_c w_m}\right)$$

- Note that the symbol error rate is upper bounded due to repetition code nature of the DS by

$$P_{es} \le \sum_{m=t+1}^{n} \binom{n}{m} p^m (1-p)^{n-m}, t = \left\lfloor \tfrac{1}{2}(d_{\min} - 1) \right\rfloor$$

where *t* denotes the number of erroneous bits that can be corrected in the coded word

*For further background, see J.G.Proakis: Digital Communications (IV Ed), Section 13.2

Example: Error Rate of Uncoded Binary BPSK-DS

- For uncoded DS w=n, thus $R_c w = (1/n)n = 1$ and

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0} R_c w_m}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

- We note that $E_b = P_{av} T_b = P_{av} / R_b$ and $J_0 = J_{av} / W$ yielding

$$\frac{E_b}{J_0} = \frac{P_{av} / R}{J_{av} / W} = \frac{W / R}{J_{av} / P_{av}}$$

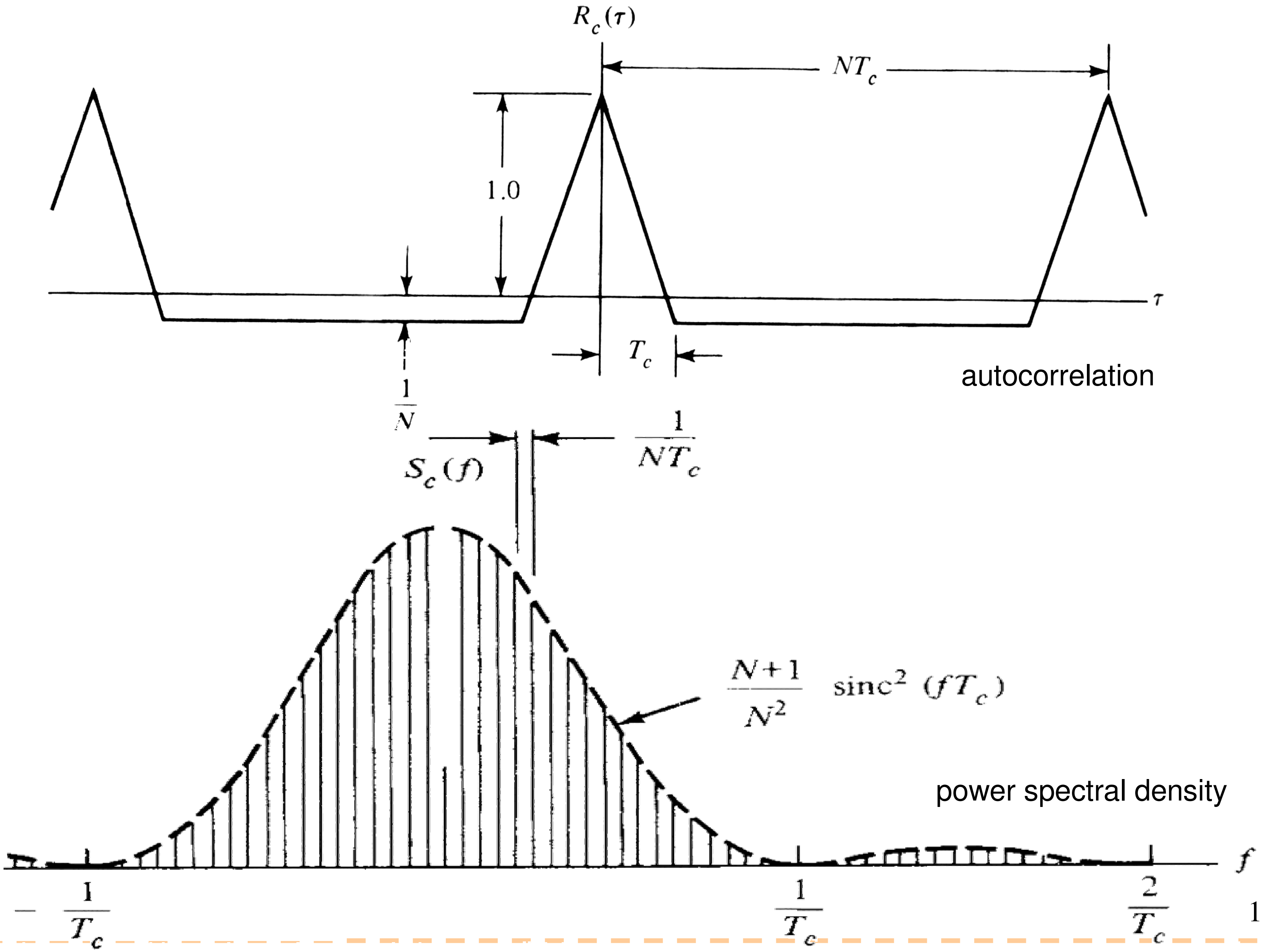
$$\Rightarrow P_e = Q\left(\sqrt{\frac{2W / R}{J_{av} / P_{av}}}\right)$$

- Therefore, we note that increasing system processing gain *W/R*, error rate can be improved

Some Cyclic Block Codes

- (n,1) **Repetition codes**. High coding gain, but low rate
- (n,k) **Hamming codes**. Minimum distance always 3. Thus can detect 2 errors and correct one error. $n=2^m-1,\ k = n - m,\ m \geq 3$
- **Maximum-length codes**. For every integer $k \geq 3$ there exists a maximum length code (n,k) with $n = 2^k - 1, d_{min} = 2^{k-1}$. Hamming codes are dual of of maximal codes.
- **BCH-codes**. For every integer $m \geq 3$ there exist a code with $n = 2^m-1$, $k \geq n - mt$ and $d_{\min} \geq 2t+1$ where t is the error correction capability
- (n,k) **Reed-Solomon (RS) codes**. Works with k **symbols** that consist of m bits that are encoded to yield code words of n **symbols**. For these codes $n = 2^m - 1$, number of check symbols $n - k = 2t$ and $d_{\min} = 2t+1$
- Nowadays BCH and RS are very popular due to large d_{min}, large number of codes, and easy generation
- For further code references have a look on self-study material!

Maximal Length Codes



Maximal Length Codes (cont.)

- Have **very good autocorrelation** but cross correlation not granted
- Are **linear,cyclic block codes** - generated by feedbacked shift registers
- Number of available codes* depends on the number of shift register stages: 5 stages->6 codes, 10 stages ->60 codes, 25 stages ->1.3x10^6 codes
- Code generator design based on tables showing tap feedbacks:

TABLE 3-5. Primitive Polynomials Having Degree $r \leq 34$ (continued)

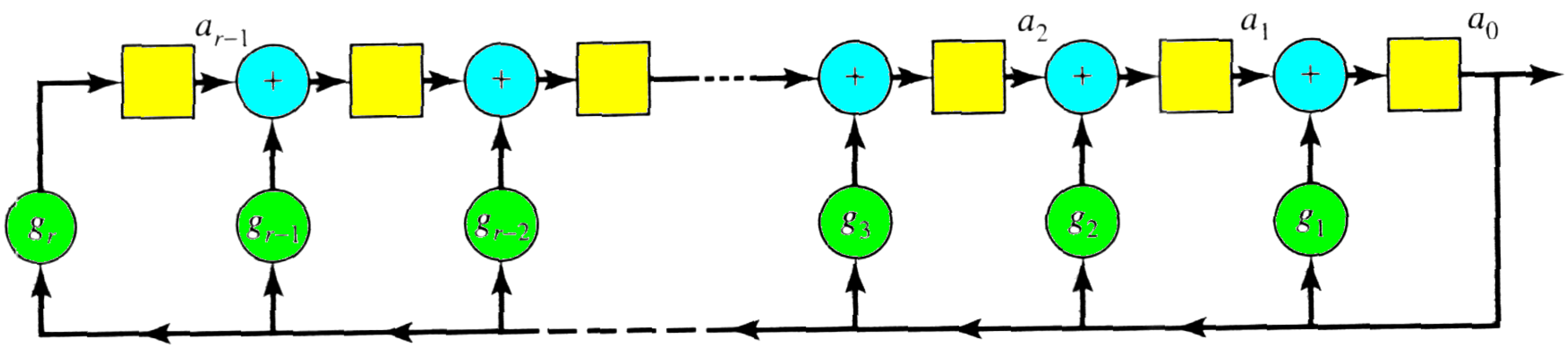
Degree	Octal Representation of Generator Polynomial (g_0 on right to g_r on left)
6	[103]*, [147], [155]
7	[211]*, [217], [235], [367], [277], [325], [203]*, [313], [345]
8	[435], [551], [747], [453], [545], [537], [703], [543]
9	[1021]*, [1131], [1461], [1423], [1055], [1167], [1541], [1333], [1605], [1751], [1743], [1617], [1553], [1157]
10	[2011]*, [2415], [3771], [2157], [3515], [2773], [2033], [2443], [2461], [3023], [3543], [2745], [2431], [3177]
11	[4005]*, [4445], [4215], [4055], [6015], [7413], [4143], [4563], [4053], [5023], [5623], [4577], [6233], [6673]

For the formula see: Peterson, Ziemer: “Introduction to Spread Spectrum Communication”, p. 121

Design of Maximal Length Generators by a Table Entry

- Feedback connections can be written directly from the table:

3			6			7			octal
0	1	1	1	1	0	1	1	1	binary
	↓	↓	↓	↓	↓	↓	↓	↓	
	g_7	g_6	g_5	g_4	g_3	g_2	g_1	g_0	coefficient



Other Spreading Codes

- Walsh codes: Orthogonal, used in *synchronous systems*, also in WCDMA downlink
- Generation recursively: $H_0 = [0] \quad H_n = \begin{bmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & \overline{H}_{n-1} \end{bmatrix}$
- All rows and columns of the matrix are orthogonal: $H_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$

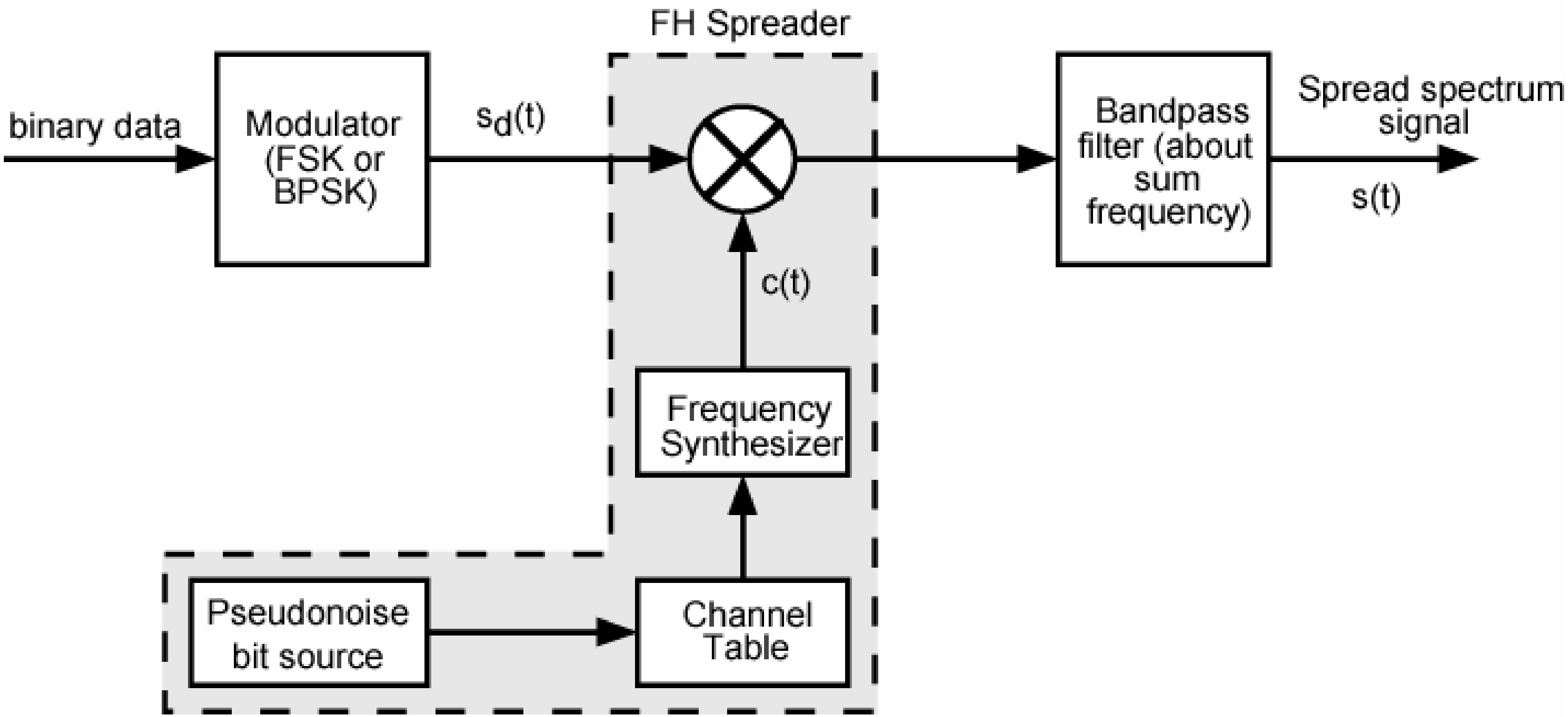
$$\Rightarrow (-1)(-1) + (-1)1 + 1(-1) + 1 \cdot 1 = 0$$

- Gold codes: Generated by summing *preferred pairs* of maximal length codes. Have a guarantee 3-level crosscorrelation: $\{-t(n)/N, 1/N, (t(n)-2)/N\}$
- For N-length code there exists $N + 2$ codes in a code family and

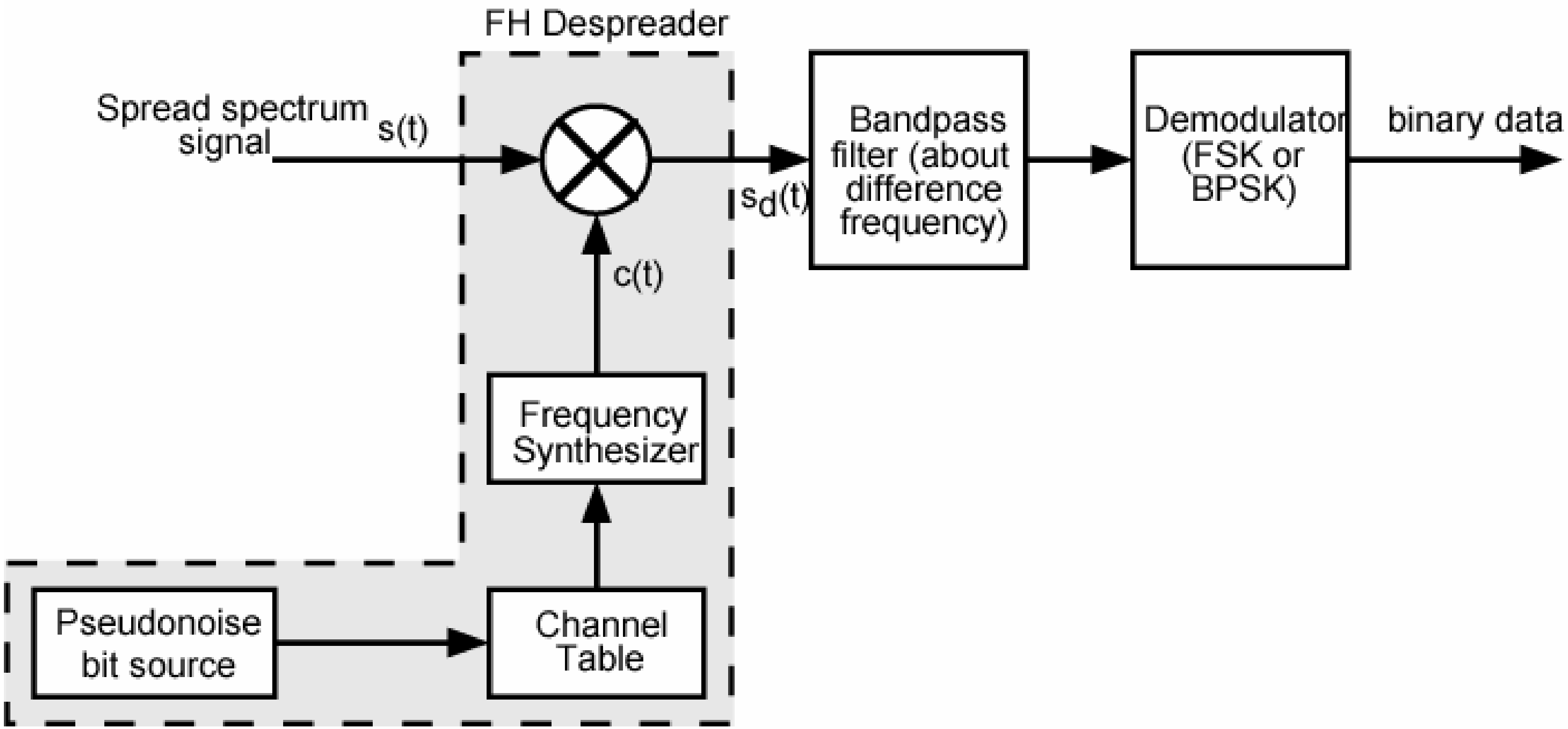
$$N = 2^n - 1 \text{ and } \quad t(n) = \begin{cases} 1 + 2^{(n+1)/2}, \text{for } n \text{ odd} \\ 1 + 2^{(n+2)/2}, \text{for } n \text{ even} \end{cases}$$

- Walsh and Gold codes are used especially in multiple access systems
- Gold codes are used in *asynchronous communications* because their crosscorrelation is quite good as formulated above

Frequency Hopping Spread Spectrum System (Transmitter)



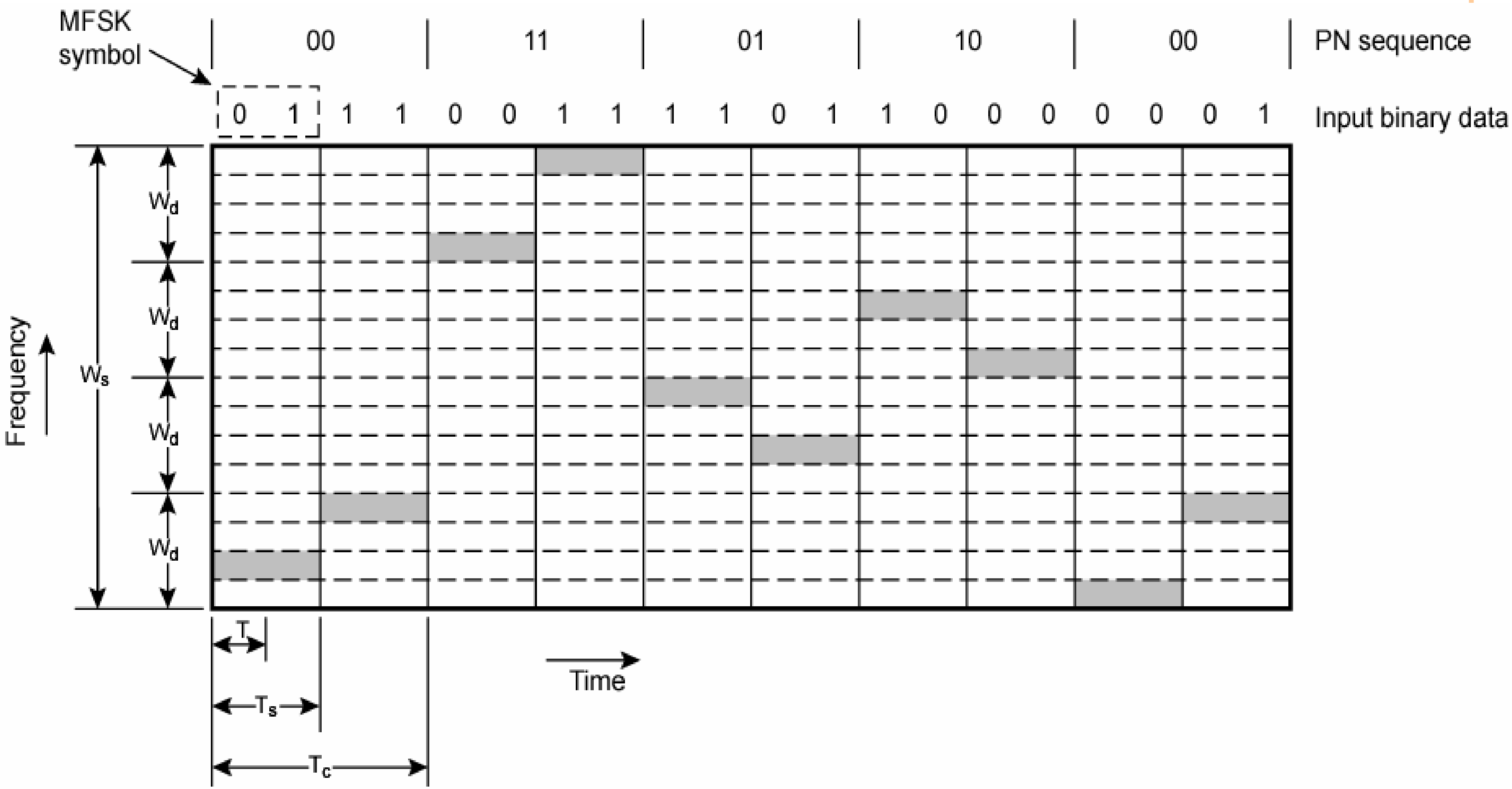
Frequency Hopping Spread Spectrum System (Receiver)



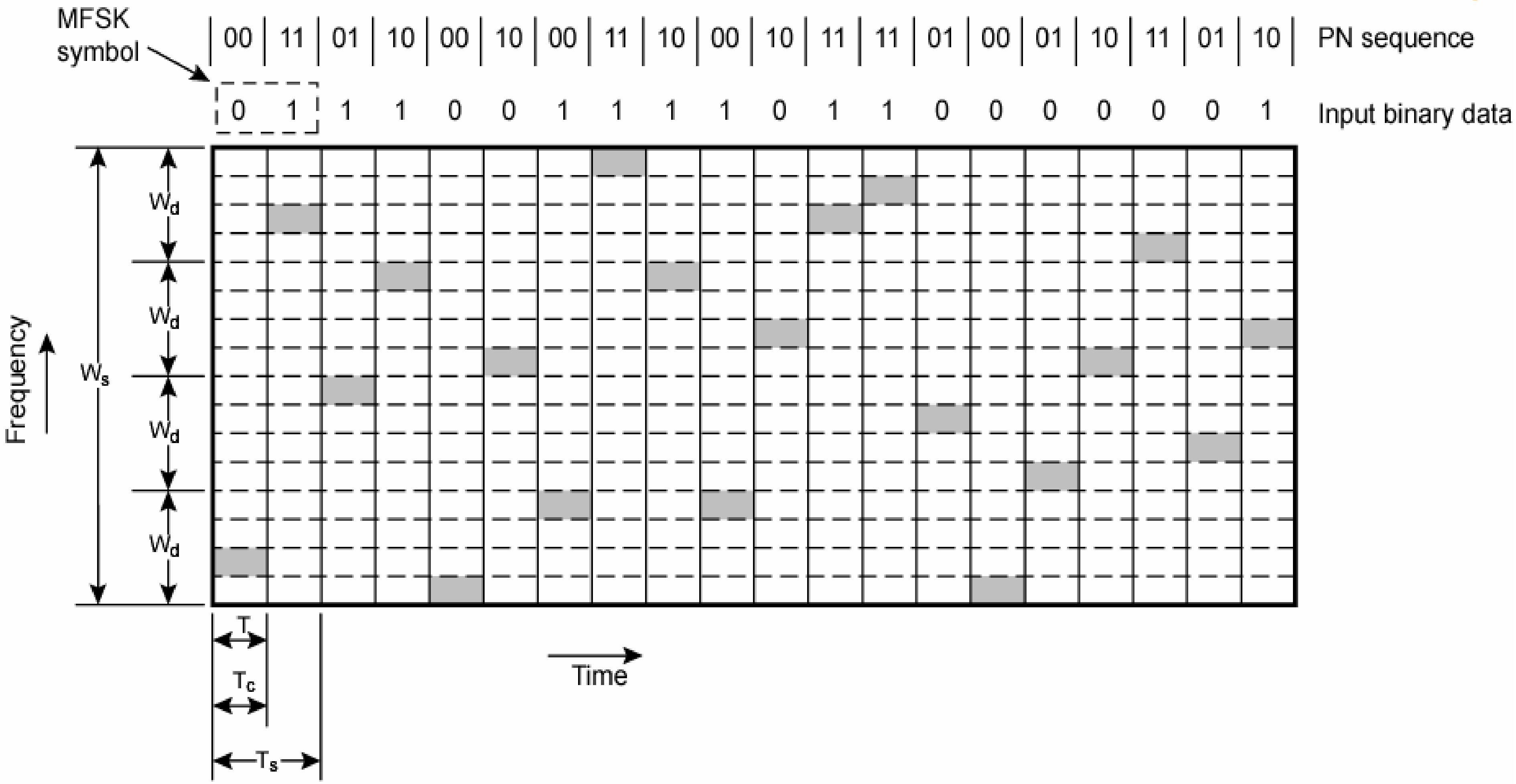
Slow and Fast FHSS

- Frequency shifted every T_c seconds
- Duration of signal element is T_s seconds
- Slow FHSS has $T_c \geq T_s$
- Fast FHSS has $T_c < T_s$
- Generally fast FHSS gives improved performance in noise (or jamming)

Slow Frequency Hop Spread Spectrum Using MFSK (M=4, k=2)



Fast Frequency Hop Spread Spectrum Using MFSK (M=4, k=2)



Error Rate in Frequency Hopping

- If there are multiple hops/symbol we have a fast-hopping system. If there is a single hop/symbol (or below), we have a slow-hopping system.
- For slow-hopping non-coherent FSK-system, binary error rate is

$$P_e = \tfrac{1}{2}\exp(-\gamma_b/2), \gamma_b = E_b/N_0$$

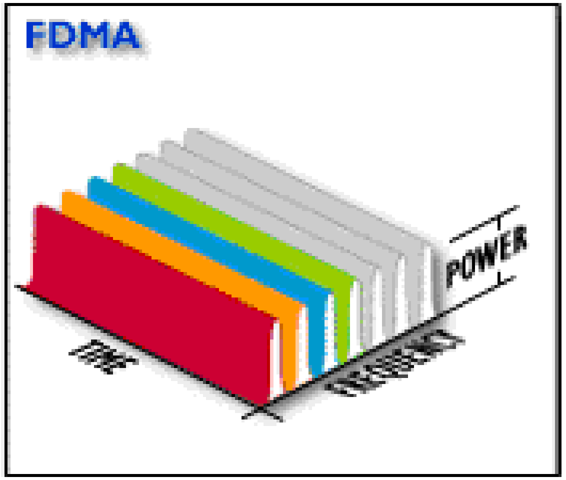
- A fast-hopping FSK system is a diversity-gain system. Assuming non-coherent, square-law combining of respective output signals from matched filters yields the binary error rate (with L hops/symbol)

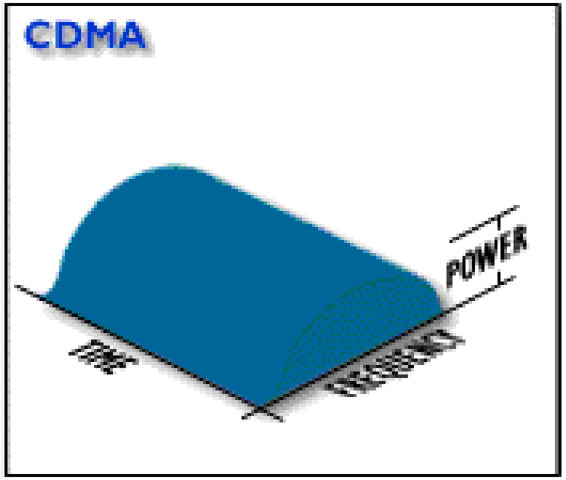
$$P_e = \frac{1}{2^{2L-1}}\exp(-\gamma_b/2)\sum_{i=0}^{L-1} K_i(\gamma_b/2)^i, \gamma_b = L\gamma_c$$

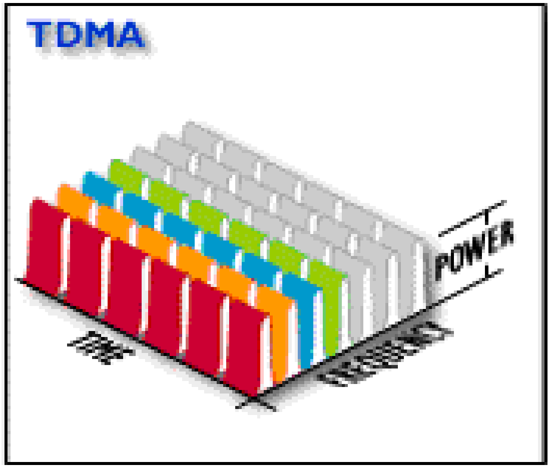
$$K_i = \frac{1}{i!}\sum_{r=0}^{L-1-i}\binom{2L-1}{r}$$

(For further details, see J.G.Proakis: Digital Communications (IV Ed), Section 13.3)

Multiple access: FDMA, TDMA and CDMA

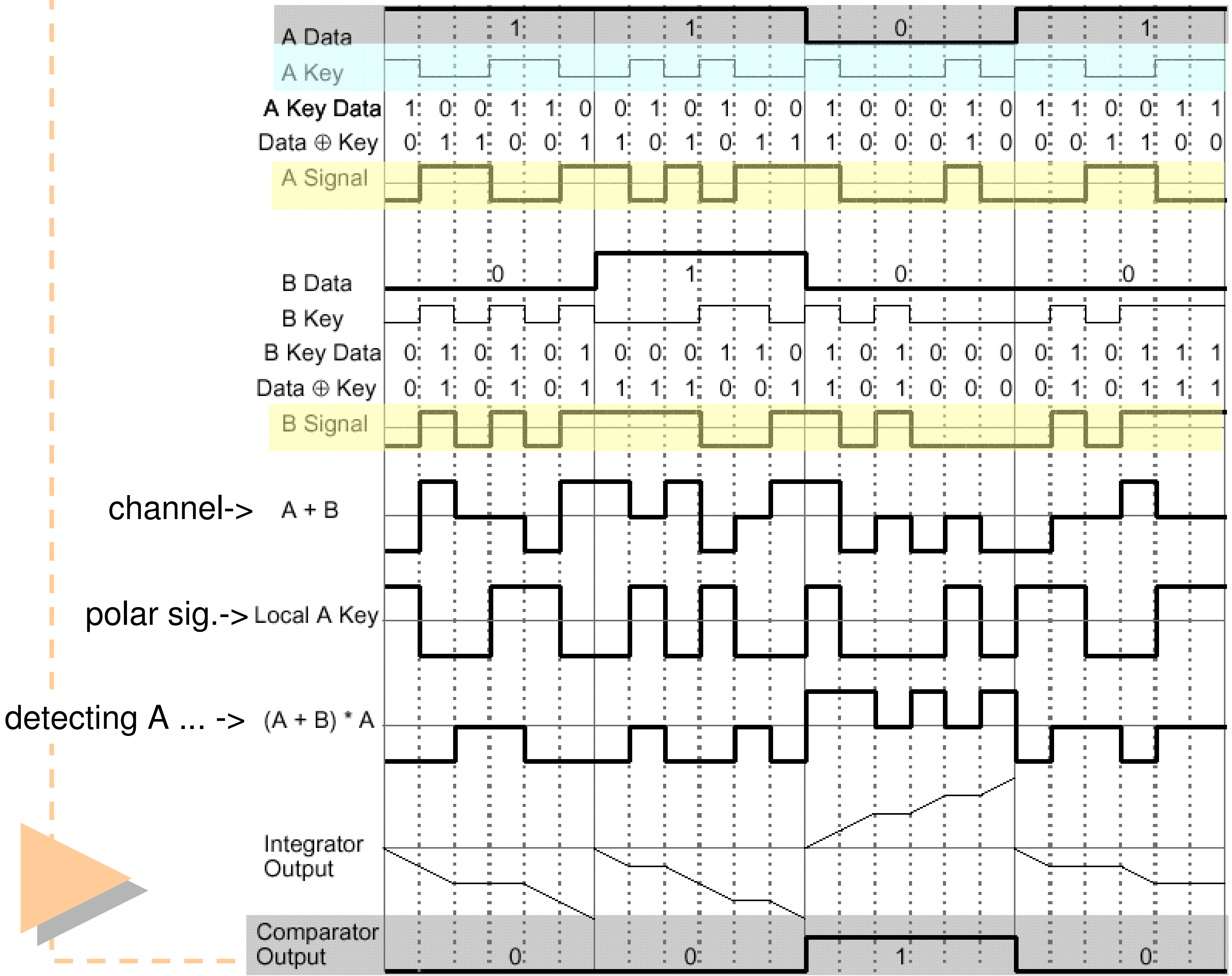






- FDMA, TDMA and CDMA yield conceptually the same capacity
- However, in wireless communications CDMA has improved capacity due to
  - statistical multiplexing
  - graceful degradation
- Performance can still be improved by adaptive antennas, multiuser detection, FEC, and multi-rate encoding

Example of DS multiple access waveforms



FDMA, TDMA and CDMA compared (cont.)

- TDMA and FDMA principle:
  - TDMA allocates a time instant for a user
  - FDMA allocates a frequency band for a user
  - CDMA allocates a code for user
- CDMA-system can be *synchronous* or *asynchronous*:
  - Synchronous CDMA can not be used in multipath channels that destroy code orthogonality
  - Therefore, in wireless CDMA-systems as in IS-95,cdma2000, WCDMA and IEEE 802.11 user are asynchronous
- Code classification:
  - Orthogonal, as Walsh-codes for orthogonal or near-orthogonal systems
  - Near-orthogonal and non-orthogonal codes:
    - Gold-codes, for asynchronous systems
    - Maximal length codes for asynchronous systems

Variable Data Rate Services

- Two ways to provide higher and variable data rate services:
  - Multi-code CDMA
    - Multiple Orthogonal Constant Spreading Factor (OCSF) codes
  - OVSF-CDMA
    - Single Orthogonal Variable Spreading Factor (OVSF) code

Spreading Operation

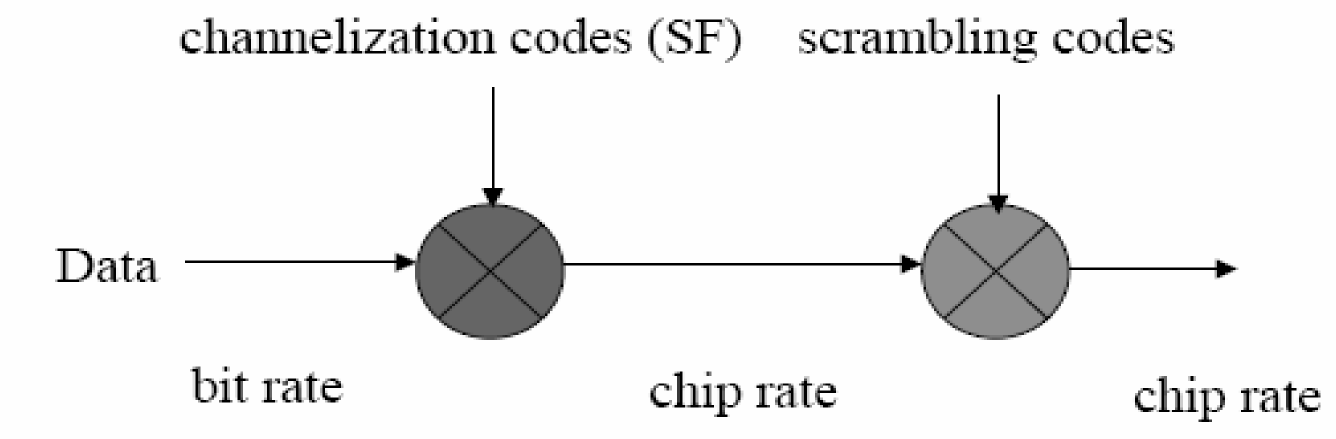
- Spreading means increasing the signal bandwidth
- Strictly speaking, spreading includes two operations:

(1) Channelization (increases signal bandwidth)

- using orthogonal codes

(2) Scrambling (does not affect the signal bandwidth)

- using pseudo noise codes



- Channelization codes are orthogonal codes
  - Separates transmissions from the same source
  - Uplink: used to separate different physical channels from the same UE – voice and data session
  - Downlink: used to separate transmissions to different physical channels and different UEs
  - UMTS uses orthogonal variable spreading codes
- Scrambling (pseudonoise scrambling)
  - Applied on top of channelization spreading
  - Separates transmissions from different sources
  - Uplink effect: separate mobiles from each other
  - Downlink effect: separate base stations from each other

WCDMA Parameters

Channel B.W	5 MHz
Forward RF Channel Structure	Direct Spread
Chip Rate	3.84 Mcps
Frame Length	10 ms (38400 chips)
No. of slots/frame	15
No. of chips/slot	2560chips (Max. 2560 bits)
Uplink SF	4 to 256
Downlink SF	4 to 512

Codes

	Channellization Code	Scrambling Code
Usage	UL: Separation of physical data and control channels from same UE DL: Separation of different users within one cell	UL: Separation of terminals DL: Separation of cells/sectors
Length	UL:4-256 chips DL:4-512 chips	38400 chips
No. of codes	No. of codes under one scrambling code= SF	UL: Several million DL: 512
Code Family	Orthogonal Variable Spreading Factor	Long 10ms code: Gold code
Increase B.W?	YES	NO

OVSF

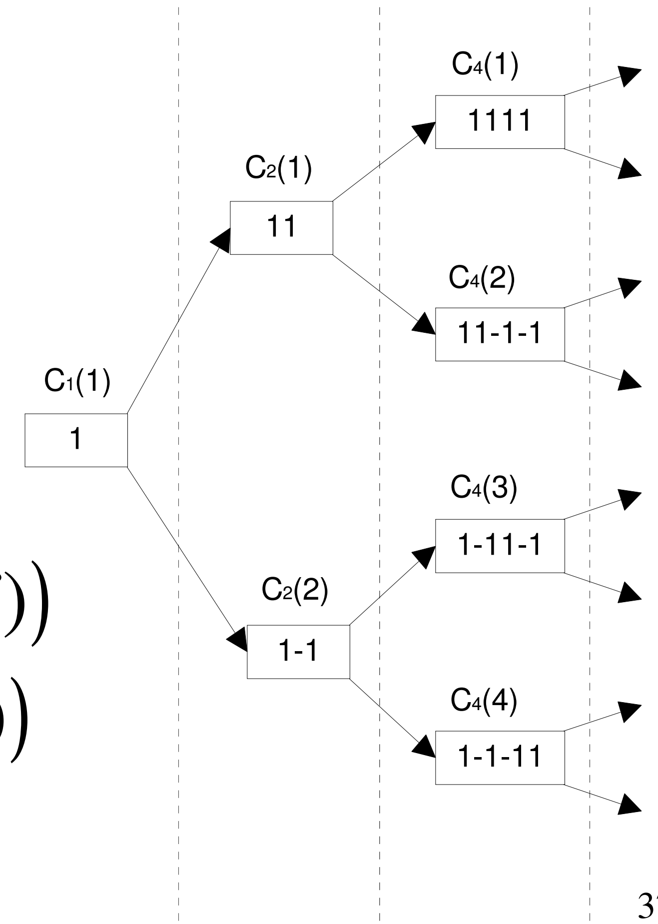
- WCDMA is used as the radio access technology in UMTS
- In WCDMA, OVSF codes are assigned to users' calls to preserve the orthogonal between users' physical channels.
- The data rate supported by an OVSF code depends on its *spreading factor* (SF).
- the rearrangeable scheme can reduce the call blocking probability.
- The drawback of the rearrangeable scheme increases the computation overhead of the system
- The nonrearrangeable schemes are considered simple and with low system overhead for the OVSF code assignment

Ortogonal Variable Spreading Factor Codes

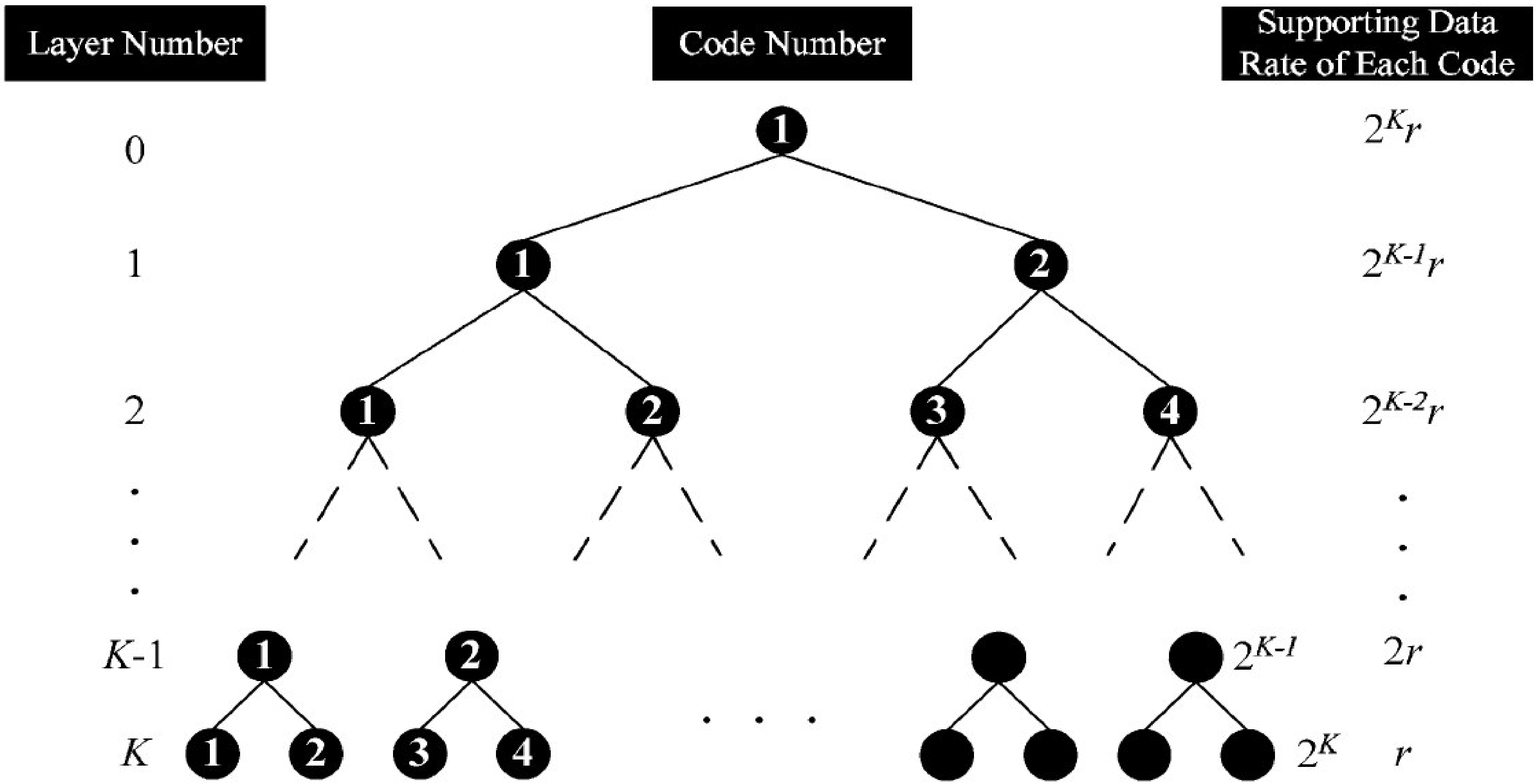
Recursive rule

$$C_1(0) = 1$$

$$C_N(i) \rightarrow \begin{cases} C_{2N}(2i-1) = \left(C_N(i), C_N(i)\right) \\ C_{2N}(2i) = \left(C_N(i), -C_N(i)\right) \end{cases}$$



Criteria for OVSF code assignment(3_1)



Criteria for OVSF code assignment(3_2)

- OVSF code have three statuses: free、busy、assignable.
  - Free: the code has not been assigned to a user.
  - Busy: the code is assigned to a user.
  - Assignable: if and only if the code and all of its ancestor and descendant OVSF codes in the tree are free.

Orthogonal Multiple Access

- requires synchronization among the users, since the waveforms are orthogonal only if they are aligned in time.

Walsh-Hadamard code

$$H_1 = [0].$$

$$H_{2n} = \begin{pmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{pmatrix}$$

To be polar, 0's are mapped to 1's and 1's are mapped to -1.

$$H_2 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \qquad H_4 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

Orthogonal Multiple Access (2)

$H_1 = [0]$.

$$H_{2n} = \begin{pmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{pmatrix}$$

$$H_2 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad H_4 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$W_{2,2}$ => (1 -1 | 1 -1) and $W_{4,3}$ => (1 1 -1 -1)

(1 x 1) + (-1 x 1) + (1 x -1) + (-1 x -1) = 1 - 1 - 1 + 1 = 0

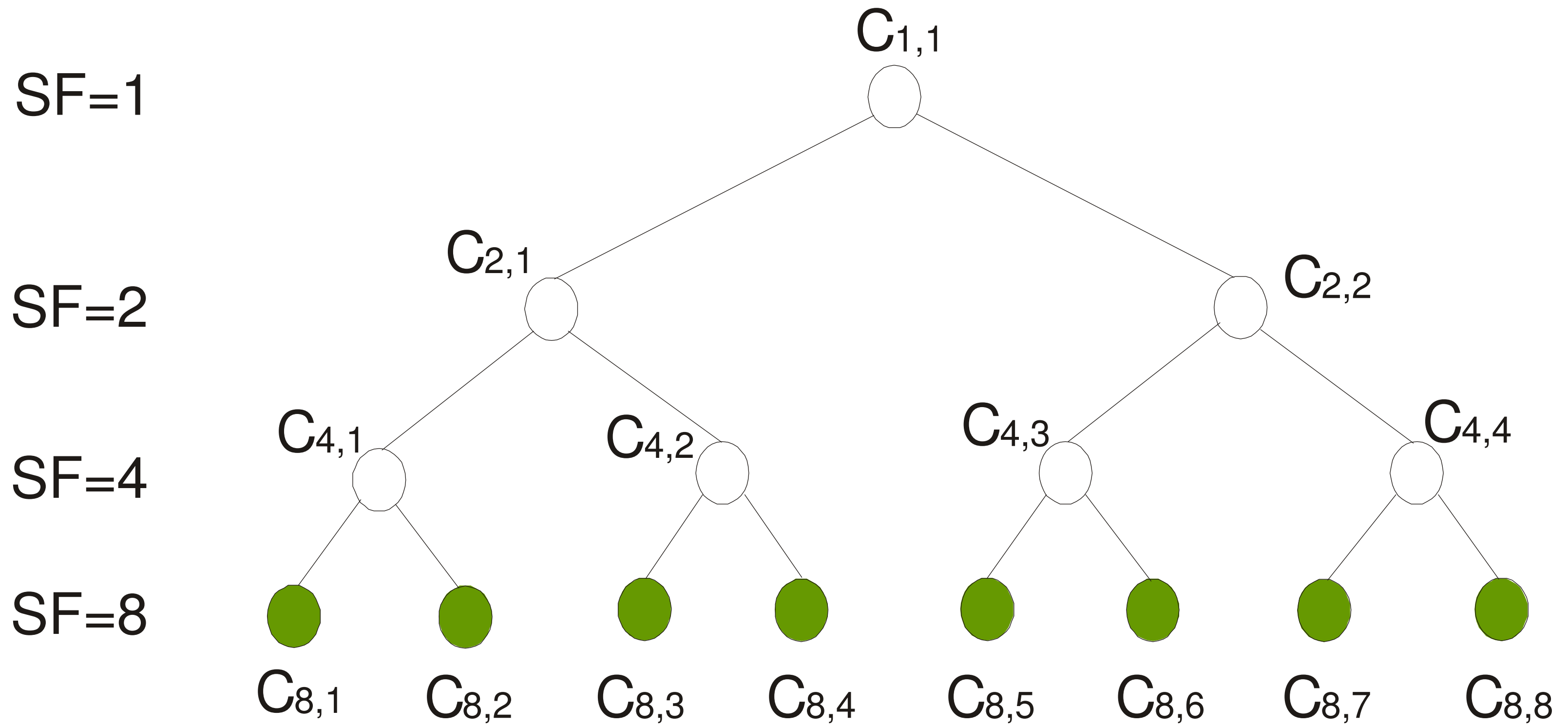
Hence, $W_{2,2}$ and $W_{4,3}$ are orthogonal.

Orthogonal Multiple Access (3)

- Disadvantage of Walsh-Hadamard code:
  1. It have more than one autocorrelation peak , therefore need an external synchronization scheme.
  2. Cross-correlation will affect it, so it is only used in synchronized CDMA
  3. Spreading is not over the whole bandwidth, instead over a number of discrete frequency-component.

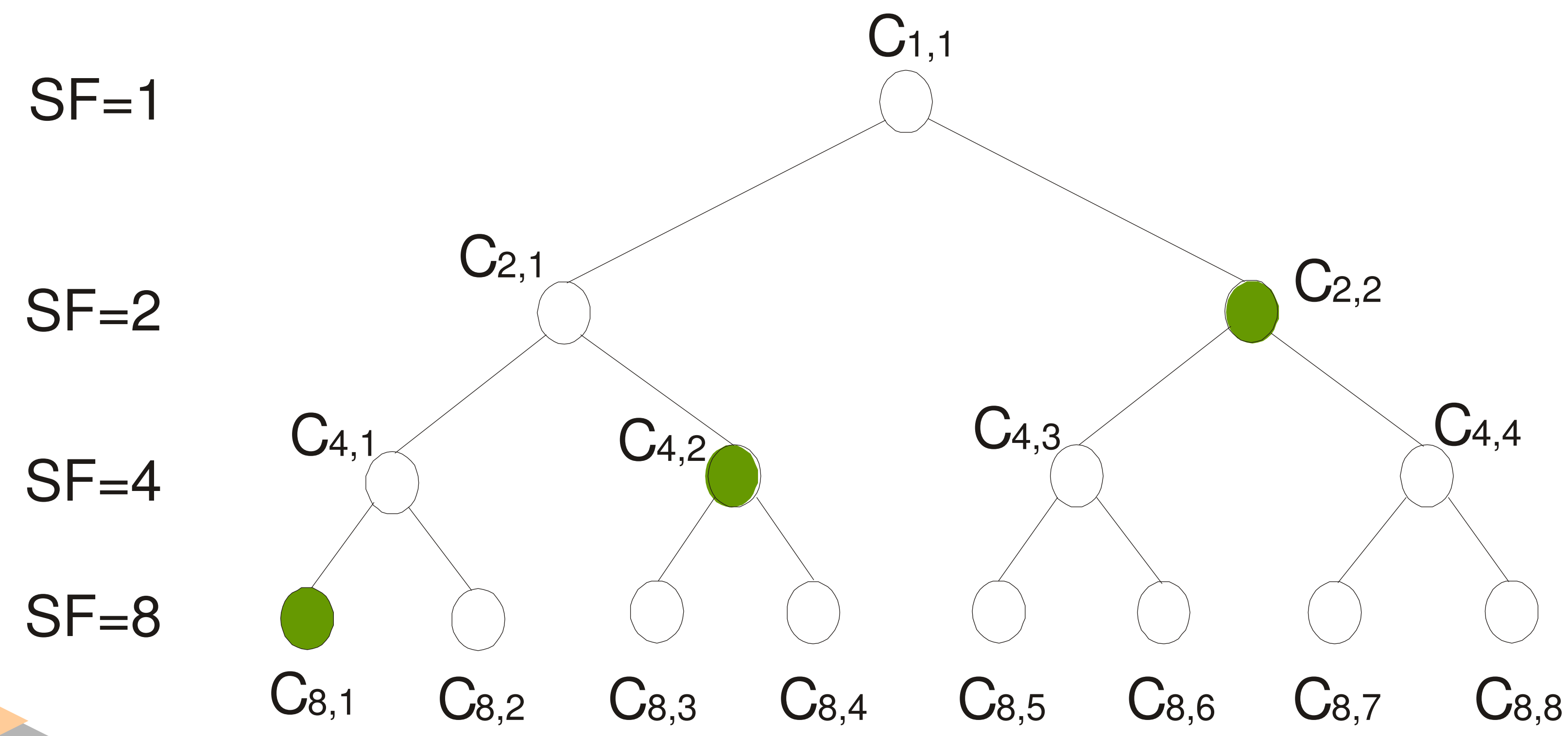
Why Orthogonal?

- All codes in the same layer are orthogonal.



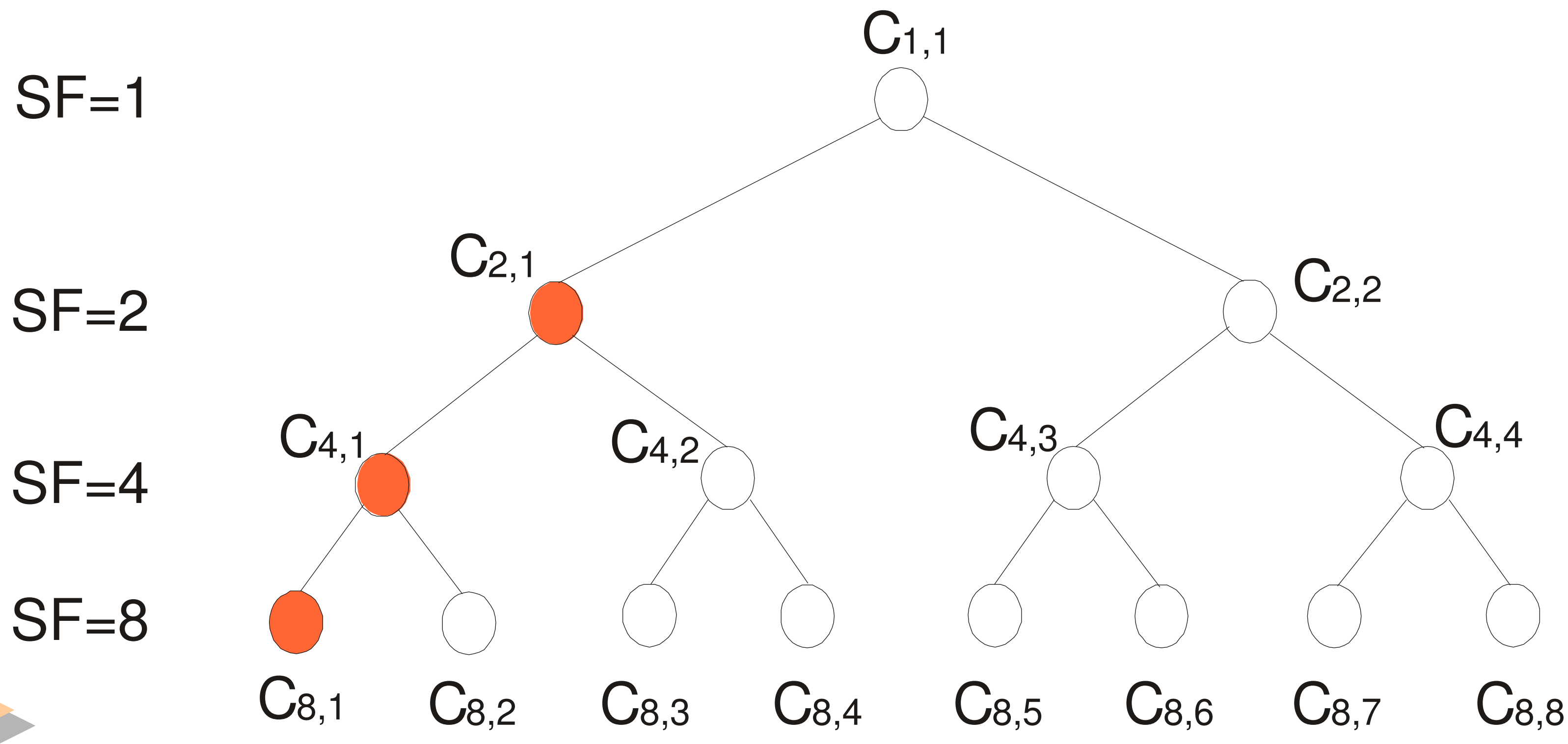
Layers in OVSF Code Tree

- Codes at different layers are orthogonal if they do not have ancestor-descendent relationship.



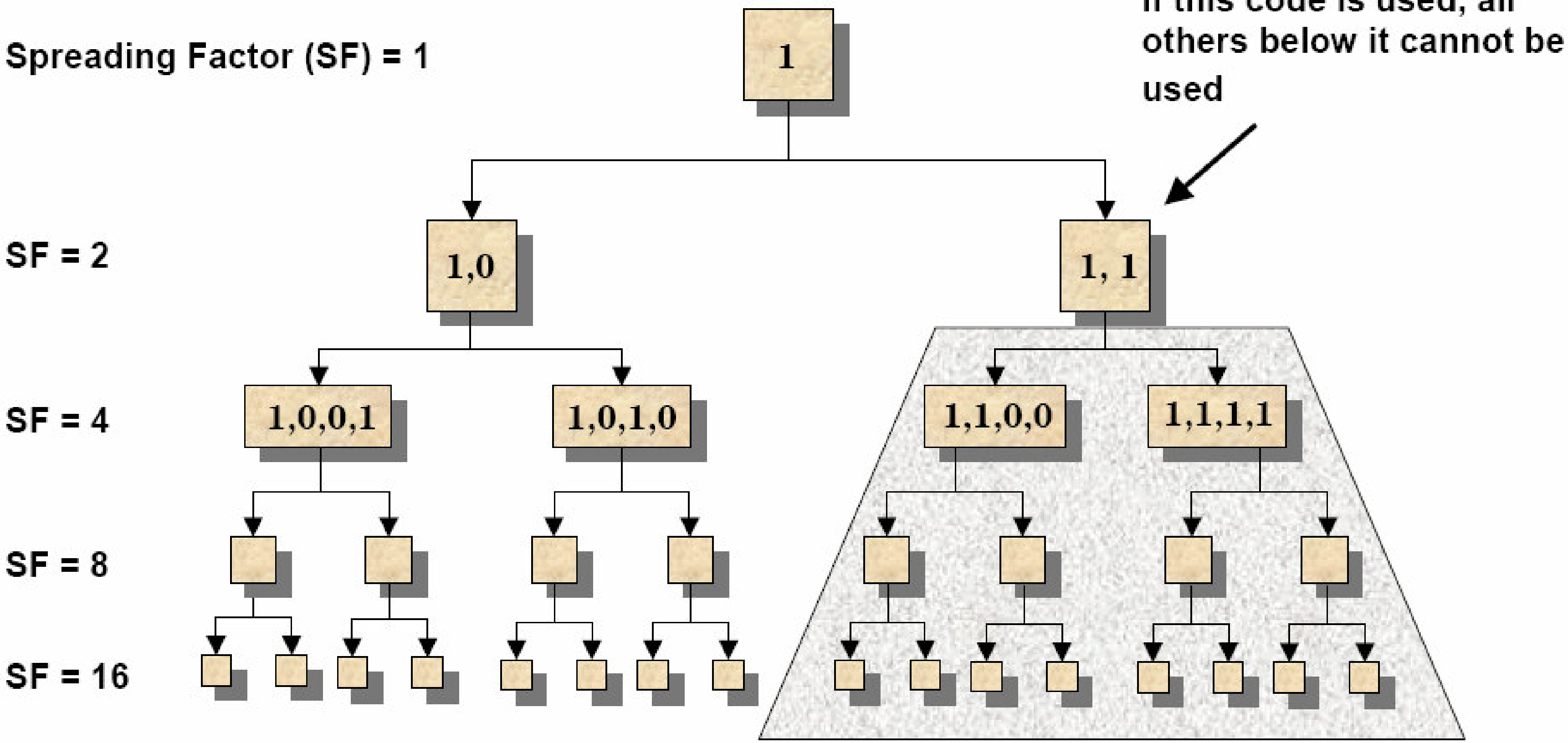
When non-orthogonal codes happens?

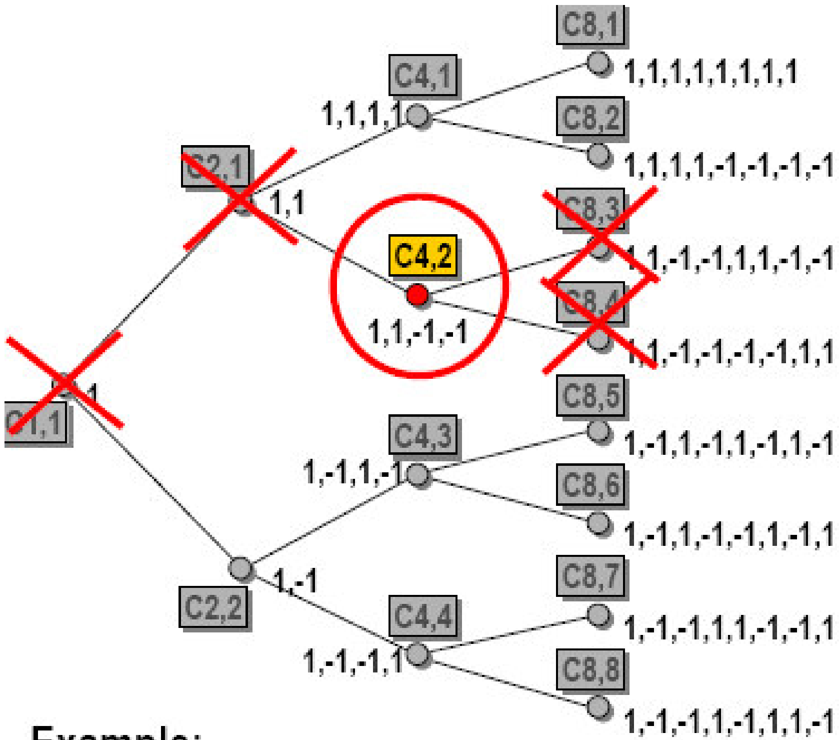
- Codes at different layers are not orthogonal if they have ancestor-descendent relationship.



Orthogonal Variable Spreading Factor codes are used to convert lower rate symbols into longer sequences at the system chip rate. The spreading factor is also the code length.

OVSF Code Tree





Bit rate	Spreading factor	Chip rate
960 kb/s	4	3.84 Mcps
480 kb/s	8	3.84 Mcps
240 kb/s	16	3.84 Mcps
120 kb/s	32	3.84 Mcps
60 kb/s	64	3.84 Mcps
30 kb/s	128	3.84 Mcps
15 kb/s	256	3.84 Mcps
7.5 kb/s	512	3.84 Mcps

bit rate * spreading factor = 3.84 Mcps

Example:

- C4,2 is assigned to a user
- Codes C8,3 and C8,4 generated from this code cannot be assigned to other users requesting lower bit rates
- Mother codes C1,1 and C2,1 cannot be assigned to users requesting higher rates

→Mobile Communications I, chapter 4.3
→Mobile Communications I, chapter 6.3
→Mobile Communications I, chapter 5.1
→Mobile Communications I, chapter 7.1

Drawbacks of Channelization Codes

Problem 1

- Networks based on WCDMA have usually a cluster size of 1
- Thus, access to the code tree must be coordinated between adjacent cells or each cell needs its own code tree

Problem 2

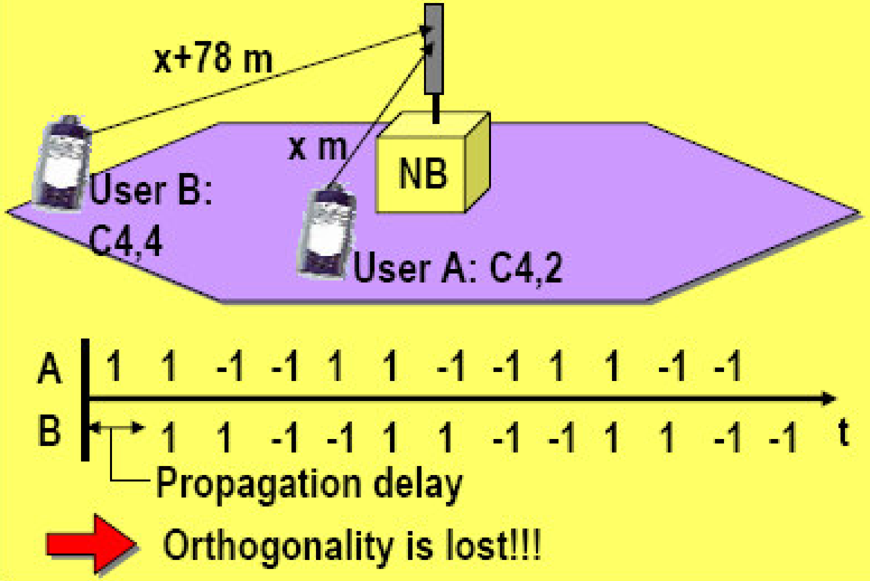
- Propagation delay of users with different distances to the node B could destroy the orthogonality of the used codes (see example)
- Codes are received asynchronously

Scrambling codes

- Sector and cell separation in the downlink
- Terminal and cell separation in the uplink
- Codes remain nearly orthogonal if received asynchronously

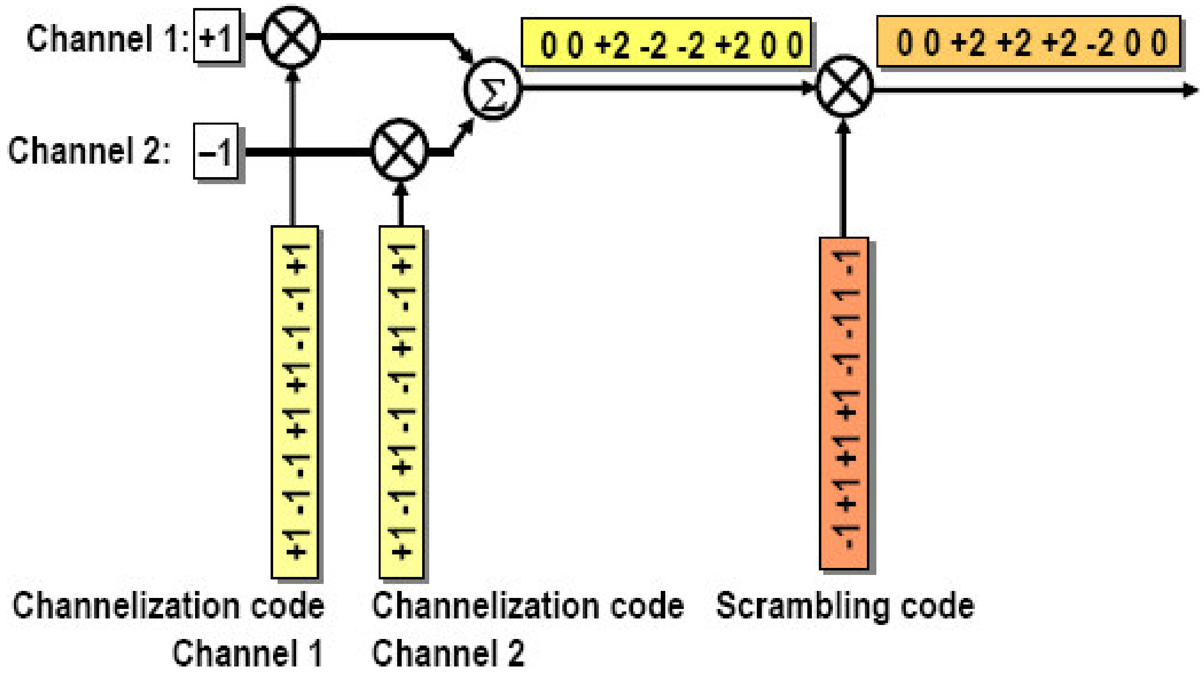
Example for (2):

- Two users A and B use channelization codes C4,2 and C4,4
- Difference in the distance to the node B is 78 m, which is covered by the signal in 0,26µs (corresponds to the duration of 1 Chip)

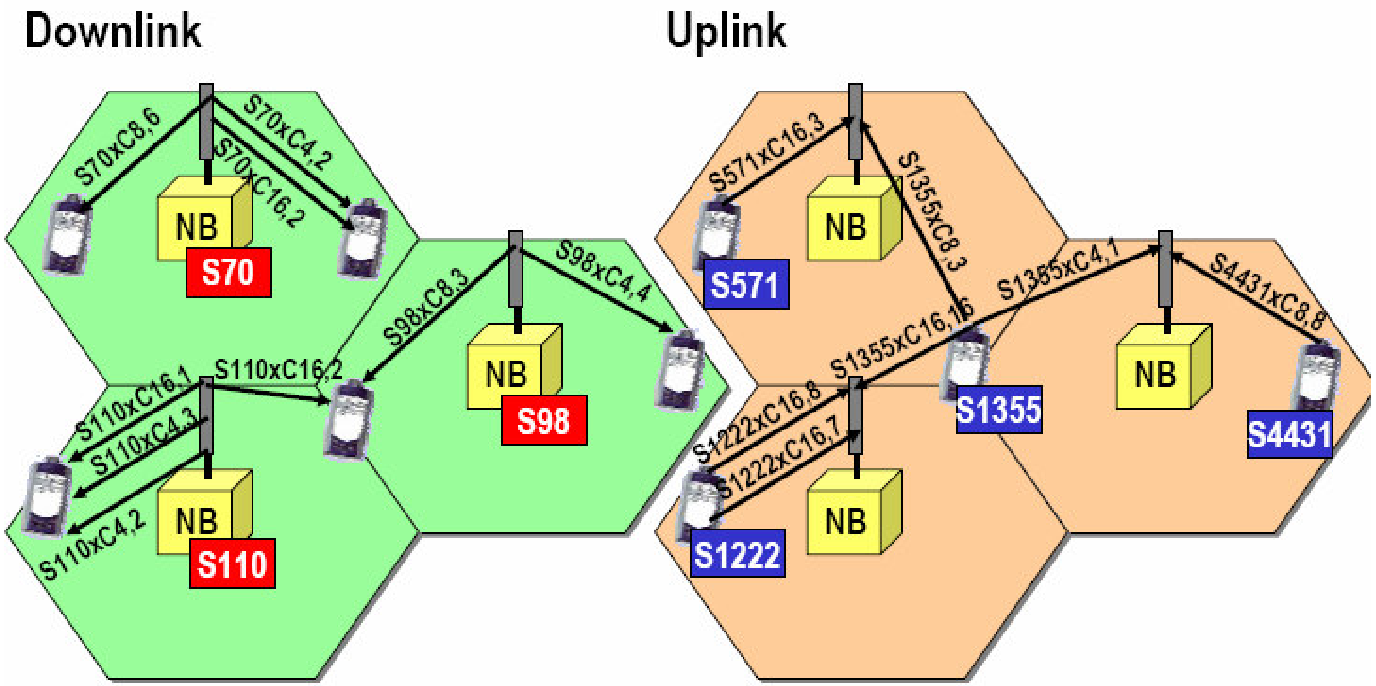


Combined Usage of Channelization and Scrambling Codes (I)

Code	Uplink direction	Downlink direction
Scrambling codes	User separation	Cell separation
Channelization codes	Data and control channels from the same terminal	Users within one cell
Spreading code	Channelization code × scrambling code	Channelization code × scrambling code



11.3 Physical Channels
Combined Usage of Channelization and Scrambling Codes (II)



Sxxx : Primary scrambling code of code set xxx

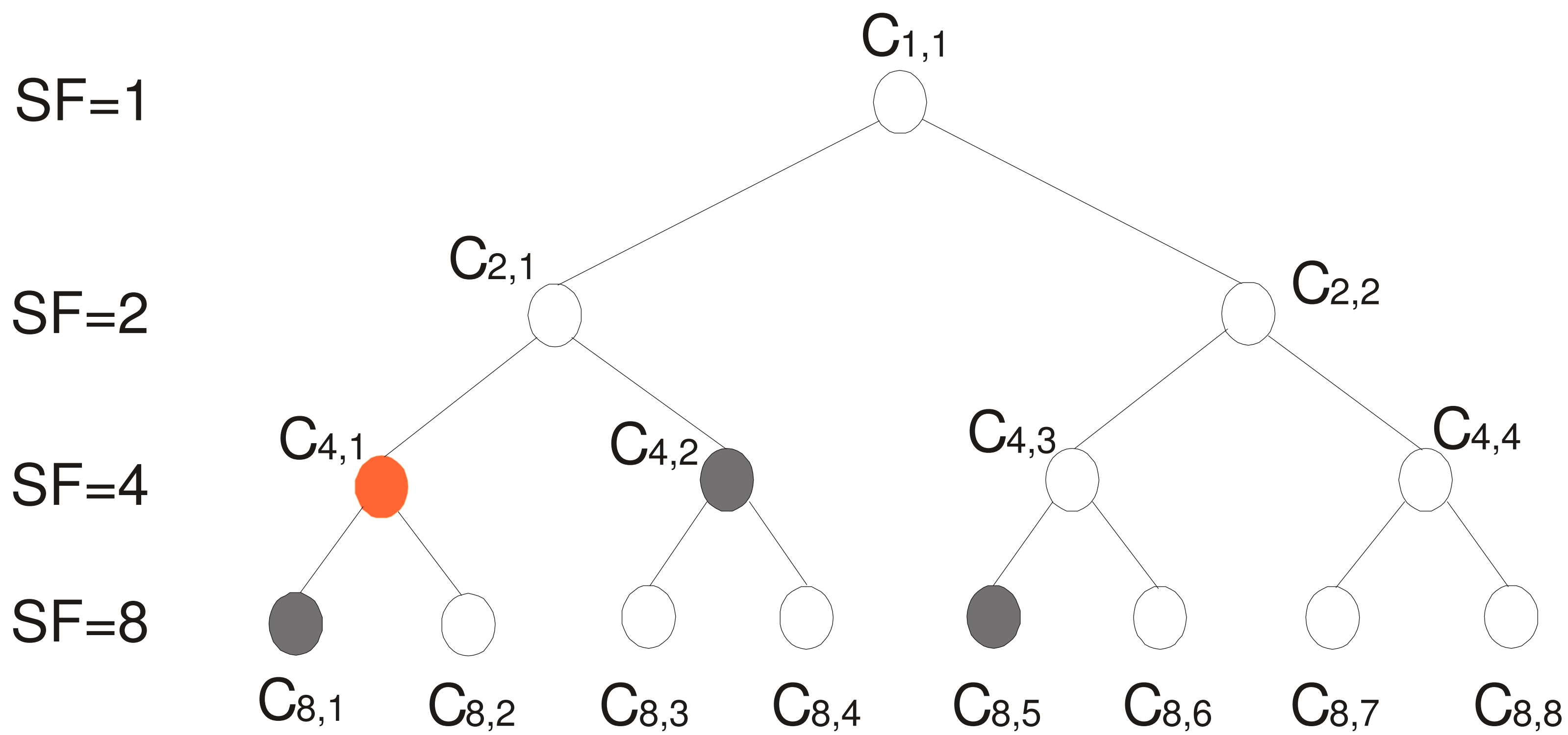
Sxxx : Terminal assigned scrambling code

→ : Signaling or traffic channel

Cx,y : yth code out of x channelization codes

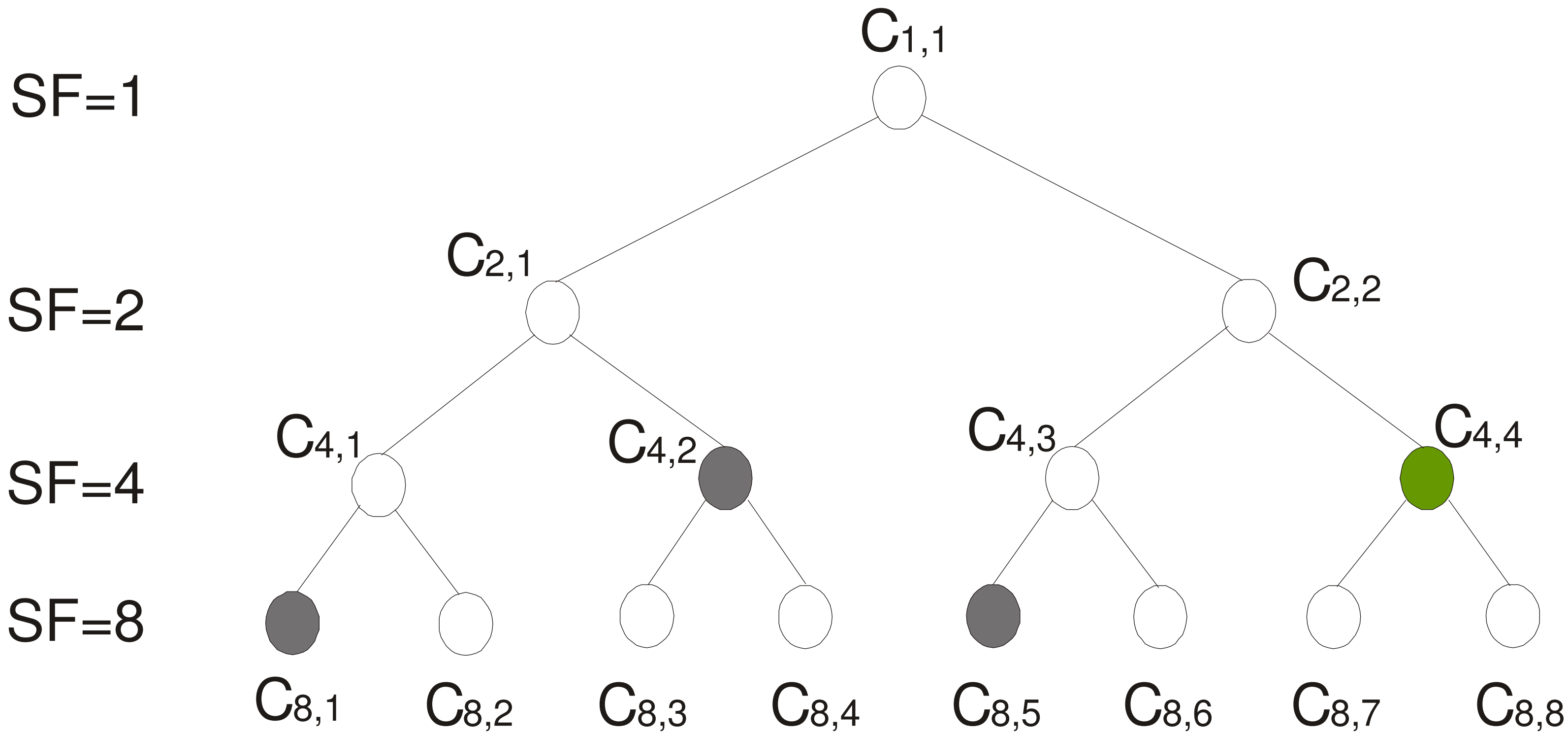
Multi-rate Assignment Issue

$C_{4,1}$ is not allowed to be assigned to a $2R_b$ request.



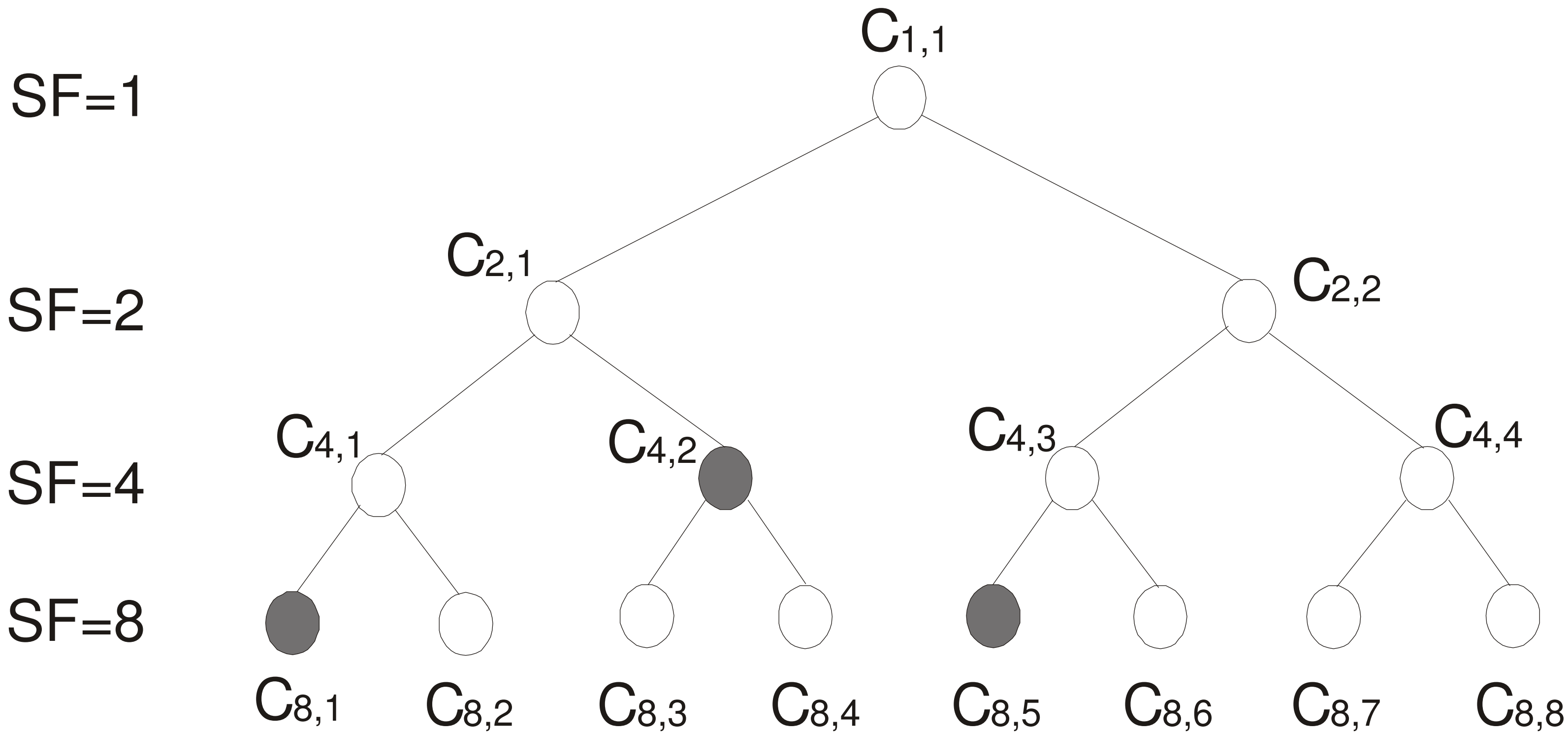
Tree Locations and Code Assignment

$C_{4,4}$ can be assigned to a $2R_b$ request.



Code Blocking

Suppose 1 code can be assigned to a user.
A request $4R_b$ will be rejected (code blocking)



Multi-code assignment

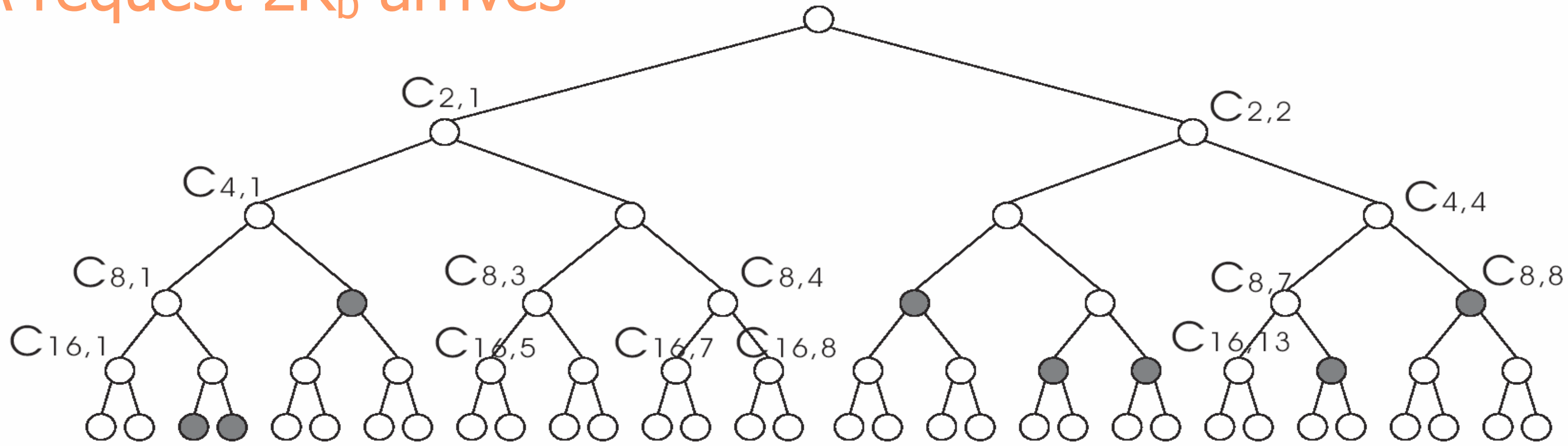
- There are three dimensions when considering the code allocation:
  - Ordering of assignment
    - Increasing or decreasing
  - Co-location of codes
    - United or separated
  - Assignment of individual codes
    - Four code assignment schemes are proposed

Individual code placement schemes

- Random
  - If there is one or more than one code in the code tree, Randomly pick anyone.
- Leftmost
  - If there is one or more than one code in the code tree, pick the leftmost one.
- Crowded-first-space
  - If there is one or more than one code in the code tree, pick the one whose ancestor code has the least free capacity.
- Crowded-first-code
  - If there is one or more than one code in the code tree, pick the one whose ancestor code is occupied by most codes.

Code assignment example (one code)

A request $2R_b$ arrives



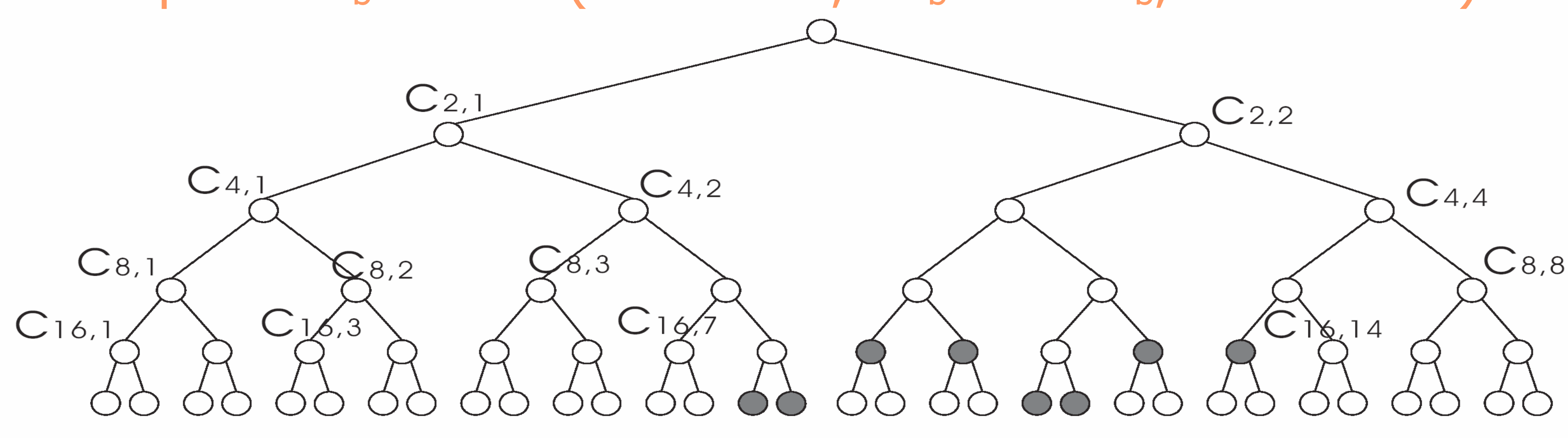
Candidate codes : $C_{16,1}$, $C_{16,5}$, $C_{16,6}$, $C_{16,7}$, $C_{16,8}$, $C_{16,13}$.

- Random
  - Any of the candidates can be picked
- Leftmost
  - $C_{16,1}$ will be picked.

- Crowded-first-space
  - $C_{16,13}$ will be picked.
- Crowded-first-code
  - $C_{16,1}$ will be picked.

Code assignment example (multi-code)

Suppose two codes can be assigned to a user.
A request $6R_b$ arrives (two codes, $4R_b$ and $2R_b$, are needed).



united assignment, decreasing order

- Leftmost
  - $\{C_{8,1}, C_{16,3}\}$
- Crowded-first-space
  - $\{C_{8,8}, C_{16,14}\}$
- Crowded-first-code
  - $\{C_{8,3}, C_{16,7}\}$

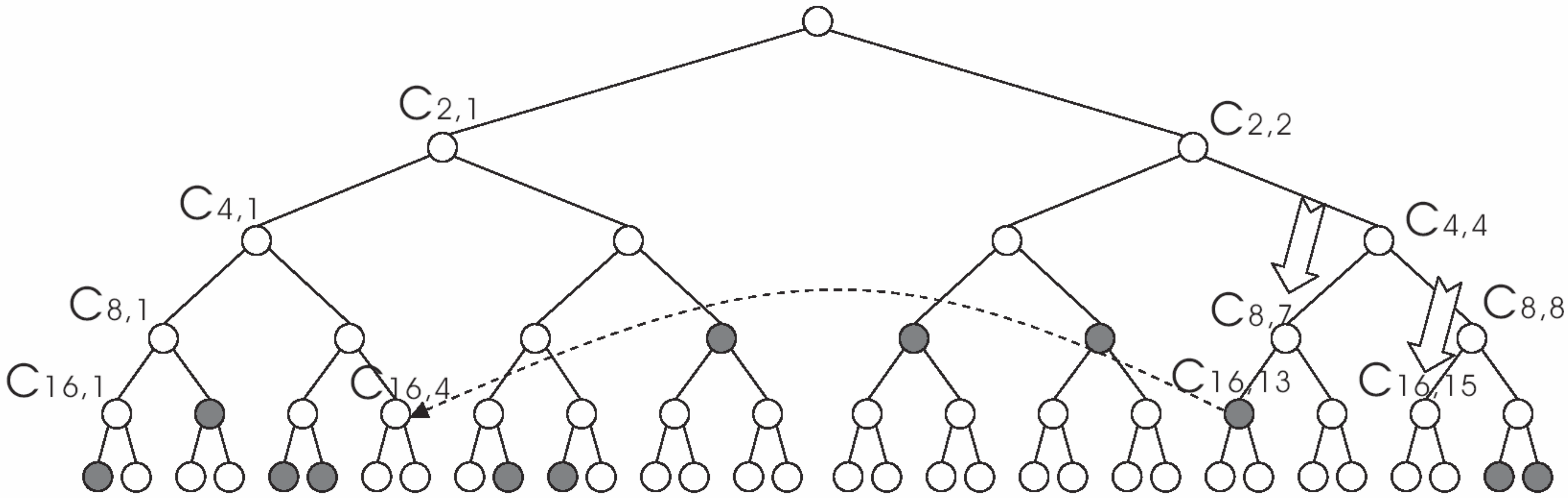
Code reassignment

- When a code tree is used for long, it is sometimes inevitable that the code tree may become fragmented .
- To solve this problem, code reassignment can be conducted to move current codes around so as to squeeze a large-enough space for the request.

Code reassignment example

Suppose two codes can be assigned to a user.

A request $6R_b$ arrives.



Multicarrier CDMA

- Multicarrier CDMA combines OFDM and CDMA
- Idea is to use DSSS to spread a narrowband signal and then send each chip over a different subcarrier
  - DSSS time operations converted to frequency domain
- Greatly reduces complexity of SS system
  - FFT/IFFT replace synchronization and despreading
- More spectrally efficient than CDMA due to the overlapped subcarriers in OFDM
- Multiple users assigned different spreading codes
  - Similar interference properties as in CDMA

Outline

1 Problem Statement and Solution Considered

2 CDMA Multiple Access Schemes

- SC DS-CDMA, MC-CDMA, and MC DS-CDMA

3 Limitations of Broadband SC DS-CDMA and MC-CDMA

4 MC DS-CDMA for Ubiquitous Broadband Communication

- Advantages in diverse broadband channels
- Improvement through TF-domain spreading

5 Conclusions

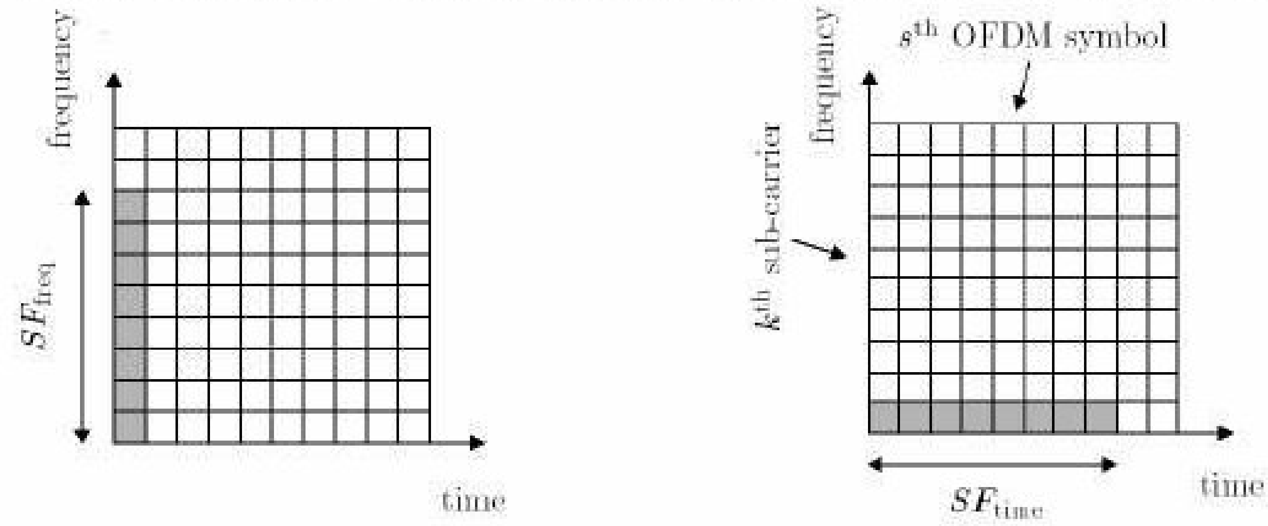
CDMA-based schemes

- Can combine concepts of CDMA and OFDM
- Reap the benefits of both techniques
- In 1993, three slightly different schemes were independently proposed:
  - MC-CDMA (Yee, Linnartz, Fettweis, and others)*
  - Multicarrier DS-CDMA (DaSilva and Sousa)*
  - MT-CDMA (Vandendorpe)

Multi-Carrier CDMA Schemes

Categorized into two Groups:

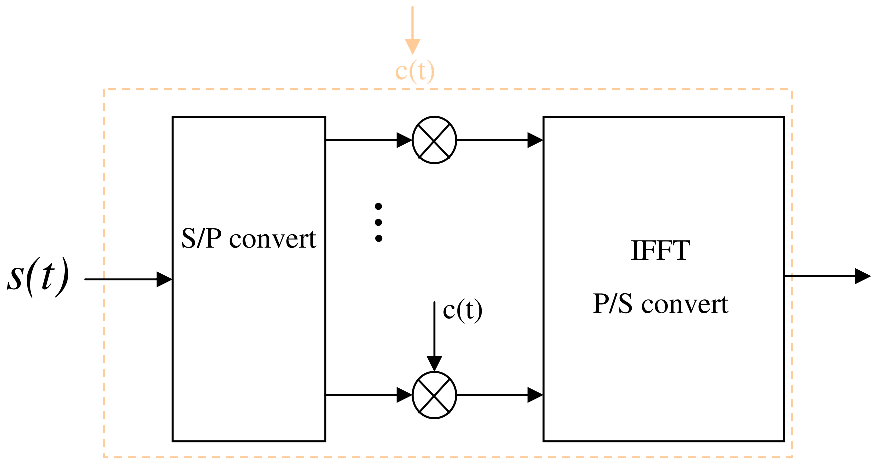
- 1st Group: Spreading operation in frequency domain
- 2nd Group: Spreading operation in time domain



- MC-CDMA (Multi-Carrier CDMA) 1
- MC DS-CDMA (Multi-Carrier DSCDMA) 2
- MT CDMA (MultiTone CDMA) 2

Multicarrier DS-CDMA

- The data is serial-to-parallel converted.
- Symbols on each branch spread in time.
- Spread signals transmitted via OFDM
- Get spreading in both time and frequency



Multi-Carrier CDMA Schemes

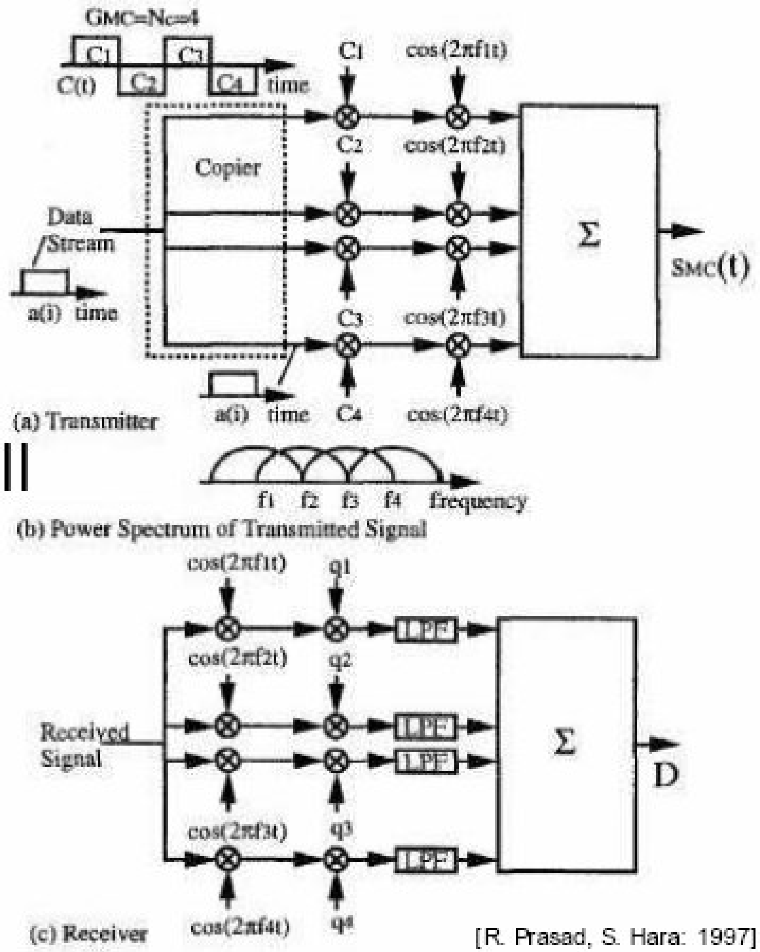
MC-CDMA (Multi-Carrier CDMA)

- Employs combination of frequency domain spreading and multi-carrier modulation
- Transmitter spreads the original data stream over different subcarriers using a given spreading code in the frequency domain

Multi-Carrier CDMA Schemes

MC-CDMA (Multi-Carrier CDMA) …….. Tx & Rx

- No of subcarriers = N_c = 4
- Received signal combined in frequency domain
- Receiver can always use all the received signal energy scattered in the frequency domain



[R. Prasad, S. Hara: 1997]

Multi-Carrier CDMA Schemes

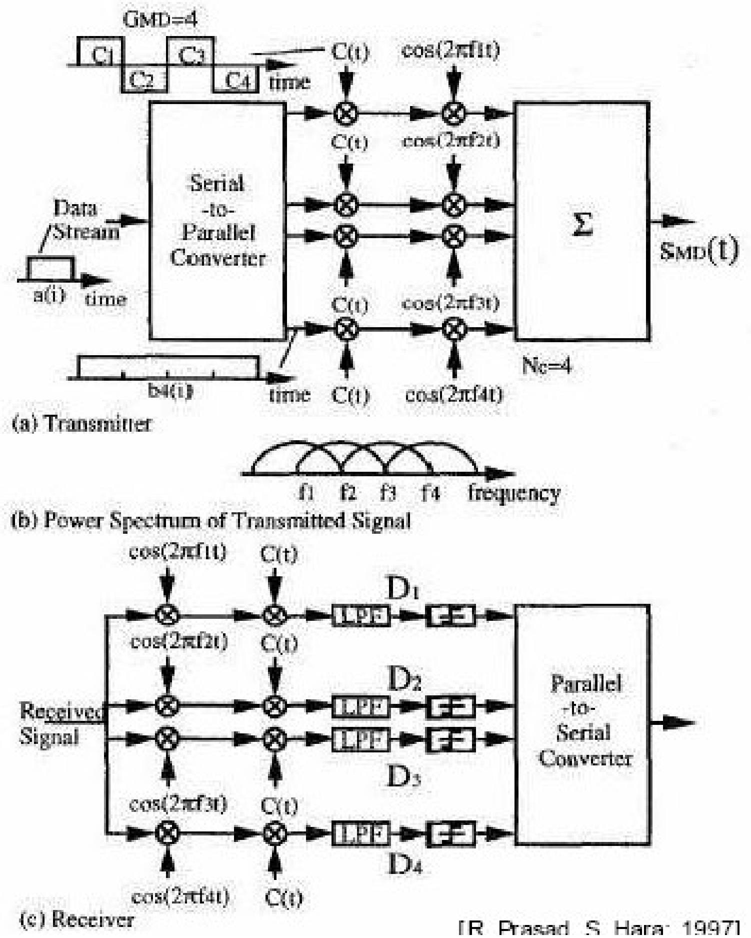
MC DS-CDMA (Multi-Carrier DS-CDMA)

- Employs combination of time domain spreading and multi-carrier modulation
- Transmitter spreads the S/P converted data streams using spreading code in the time domain
- Resulting spectrum of each subcarrier satisfies the orthogonality condition with minimum frequency separation
- Proposed for an up-link transmission channel
- With a larger subcarrier separation, can yield both frequency diversity improvement and narrowband interference separation

Multi-Carrier CDMA Schemes

MC DS-CDMA (Multi-Carrier DS-CDMA) … Tx & Rx

- No of subcarriers = Nc = 4
- Receiver composed of N_c normal coherent (Non-Rake) receivers to have frequency non-selective fading over each subcarrier
- With no FEC among subcarriers, no frequency diversity gain

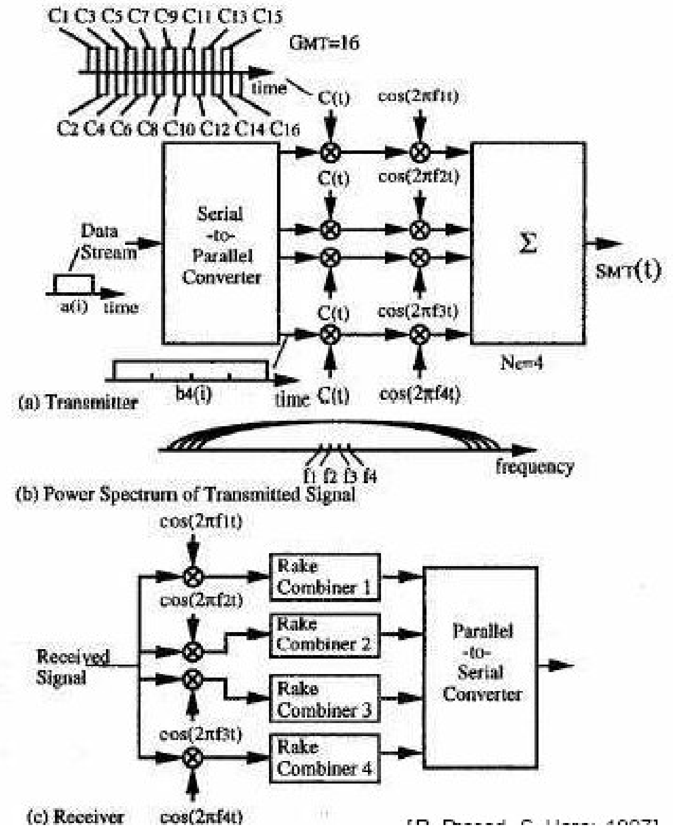


[R. Prasad, S. Hara: 1997]

Multi-Carrier CDMA Schemes

MT-CDMA (MultiTone CDMA) …….. Tx & Rx

- No of subcarriers = Nc = 4
- Suffers from inter-subcarrier interference
- Reduction of self-interference (SI) and multiple access interference (MAI) by using longer spreading codes
- Detection strategies such as Rake Combiner, DFE (Decision Feedback Equalizer), LE (linear equalizer) can be employed for uplink



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2.1 Single-Carrier Direct-Sequence CDMA

- **Transmitted signal (BPSK modulated):**

$$s_{DS}(t) = \sqrt{2P}\sum_{i=-M}^{M}\sum_{j=0}^{N-1} b[i]c[j]p_{T_{c1}}(t - iT_b - jT_{c1})\cos(2\pi f_c t)$$

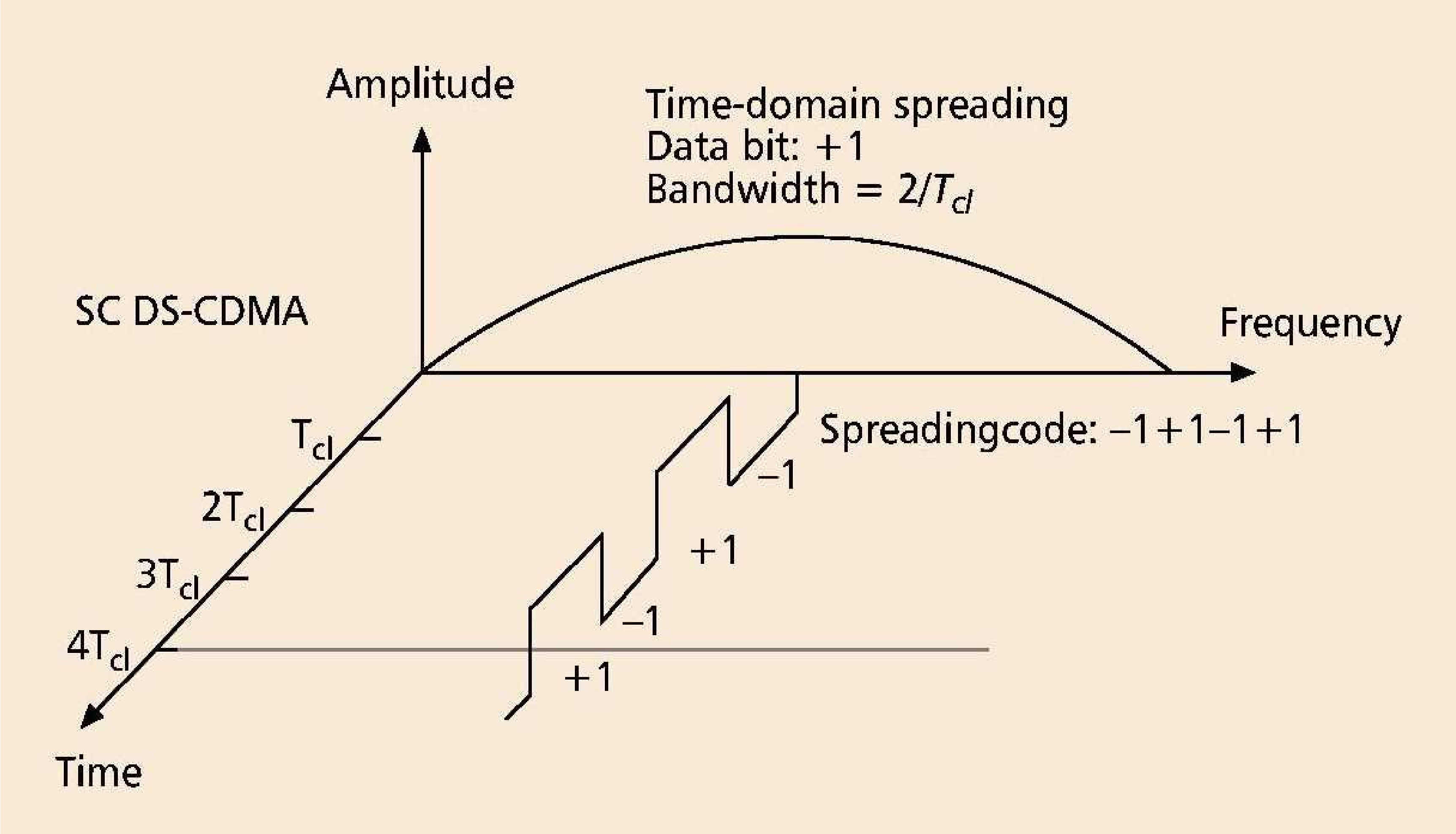
- **Spreading code in the time-domain.**

- **Processing gain is ratio of bit to chip duration.**

- **Number of users N dependents upon cross-correlation of codes.**

- **In frequency-selective fading channels, autocorrelation properties also limit number of users.**

2.2 SC DS-CDMA Illustration



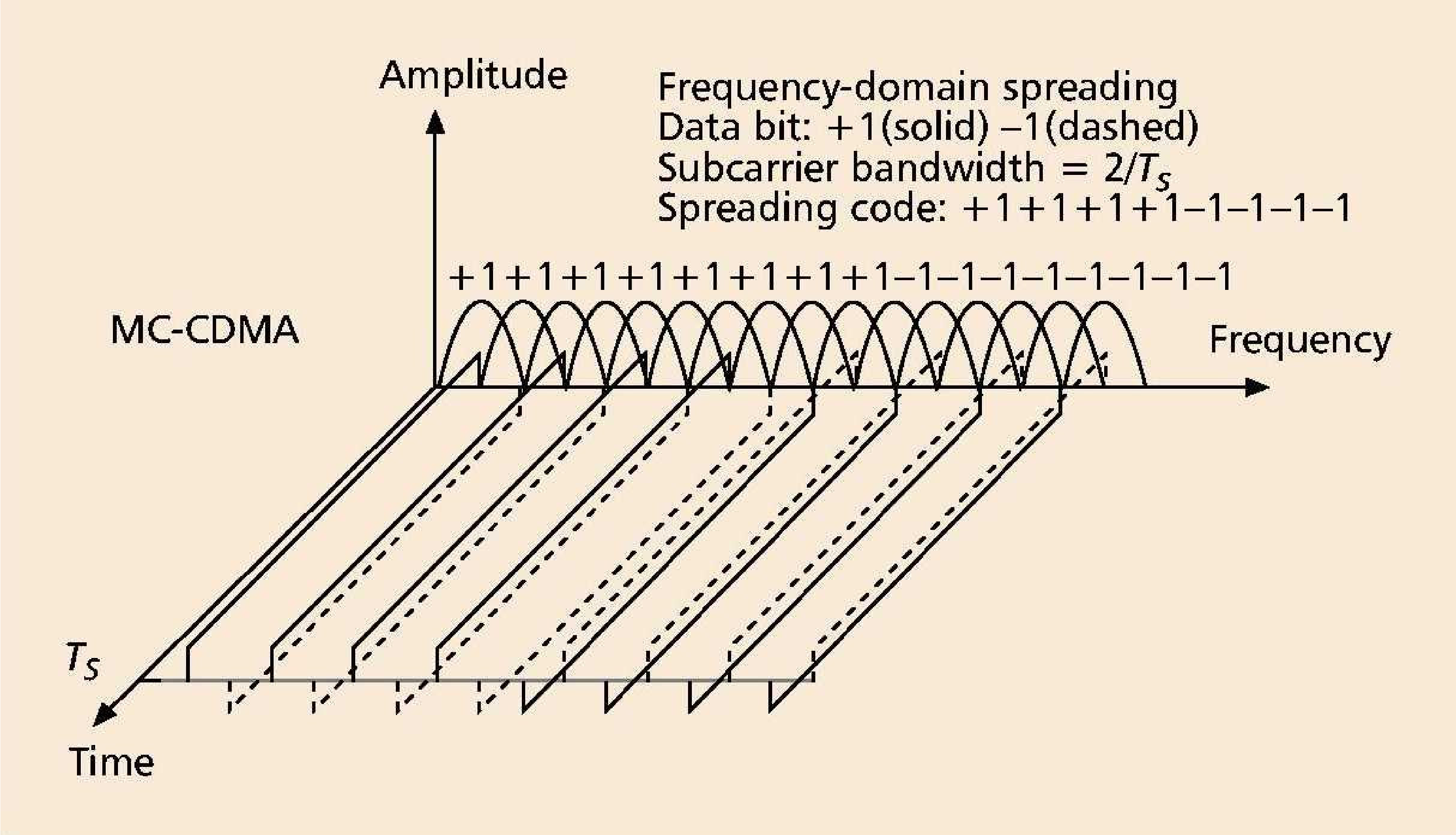
2.3 Multicarrier CDMA

- Transmitted signal:

$$s_{MC}(t) = \sqrt{\frac{2P}{UN_p}} \sum_{i=-M}^{M} \sum_{u=0}^{U-1} \sum_{j=0}^{N_p-1} b_i[u]c[j]p_{T_s}(t - iT_s)\cos[2\pi(f_c + F_{jU+u})t]$$

- Serial-to-parallel conversion generates lower-rate substreams.
- Substreams modulate orthogonal carriers at maximum spacing.
- Spreading code applied across flat-fading subchannels.
- Number of users N depends on processing gain and cross-correlation, but not on autocorrelation code characteristics.
- Alternatively, efficient IFFT/FFT implementation possible.

2.4 MC-CDMA Illustration



2.5 Multicarrier Direct-Sequence CDMA

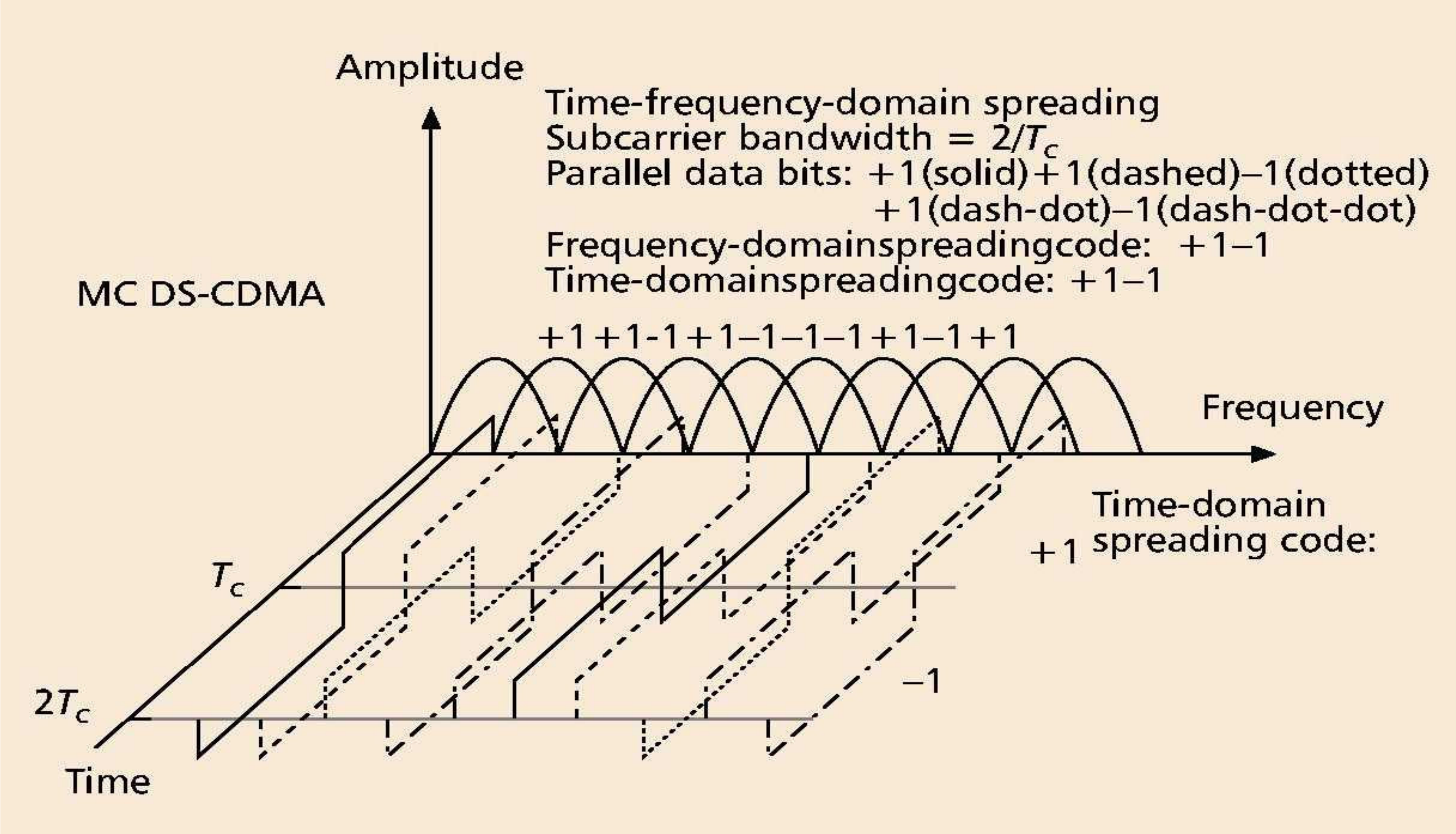
- **Transmitted signal:**

$$s_{MC}(t)=\sqrt{\frac{2P}{US}}\sum_{i=-M}^{M}\sum_{u=0}^{U-1}\sum_{s=0}^{S-1}\sum_{j=0}^{N_p-1}b_i[u]c_t[j]p_{T_c}(t-iT_s-jT_c)c_f[s]\cos[2\pi(f_c+F_{sU+u})t]$$

- **Hybrid scheme: joint spreading across time and frequency.**
- **Subcarriers not necessarily orthogonal.**
- **Processing gain usually product of T- and F-spreading codes.**
- **Number of users N depends on T- and F-domain spreading factors, cross-correlation, and autocorrelation code properties.**
- **Conventional MC DS-CDMA: only F-domain repetition.**
- **Unified family of generalized MC DS-CDMA schemes:**

  SC DS-CDMA and MC-CDMA represent the marginals.

2.6 MC DS-CDMA Illustration



2.7 Flexibility Comparison

- Flexibility (degrees of freedom) of multiple access scheme impact performance in diverse communication environments.
- Utilize during design phase or reconfiguration during operation.
- Assumptions: fixed system bandwidth, same chip waveform and BPSK modulation, common bit rate.
- NOT fixed: bit-error-rate, processing gain or number of users.
- SC DS-CDMA:
  - no degrees of freedom; system fully specified.

2.8 Flexibility Comparison Continued

- **MC-CDMA**
  - **Number of parallel bit streams (symbol bit depth U).**
  - ⇨ **Determines symbol duration and number of subcarriers.**
- **MC DS-CDMA**
  - **Chip duration influences number of subcarriers.**
  - **Number of parallel bit streams U determines F-code length.**
  - **Spacing between adjacent subcarriers: $1/T_s$ to $2/T_c$.**
  - ⇨ **Chosen to optimize BER or transmitted signal's spectrum.**
- **Parameters allow for trade-offs between spectral efficiency, BER, number of users, and degree of T- and/or F-domain spreading.**

3.1 Example: Ubiquitous Communication

◆ **Broadband system:**

- **20 MHz bandwidth to support range of services/rates.**
- **Support bit rate of 1 Mbps per user.**
- **Maximum number of users not specified.**

◆ **Channel properties:**

- **Delay spread between 0.1 and 3 μs.**

⇨ **Time-varying frequency-selective fading (ISI) channel.**

- **Different Doppler shift for lowest and highest frequencies.**

3.2 Deficiencies of SC DS-CDMA

- Severe ISI for delay spread greater 1 μs.
  - ⇨ Remedy: exploit frequency diversity using RAKE receiver.
  - × But optimal number of fingers depends on delay spread.
  - × Complex solution: adaptive MRC scheme.
- ISI destroys orthogonality of spreading codes.
  - ⇨ Remedy: Multiuser detection.
  - × But complexity increases at least linear with number of users.
  - × Requires signal processing at chip rate.

3.3 Deficiencies of MC-CDMA

- **Remove ISI by choosing many subchannels.**
  - ✗ **Problem: increased peak-to-average power ratio.**
  - ✗ **Problem: varying correlation between adjacent subcarriers.**
  - ⇨ **Diversity order changes with coherence bandwidth.**
- **Different subchannel gains destroy orthogonality in F-domain.**
  - ⇨ **Remedy: Multiuser Detection (MUD).**
  - ✗ **But complexity increases at least linear with number of users.**
  - ⇨ **Remedy: Zero-Forcing Equalizer could restore orthogonality.**
  - ✗ **Suffers from noise enhancement.**

4.1 MC DS-CDMA System Design

- Use system parameters to adjust to propagation environment.
- Goes beyond trade-off between SC DS-CDMA and MC-CDMA.
- System design for diverse channels:
  1. Choose chip duration > highest delay spread.
     - ⇨ Ensures flat-fading subcarriers.
  2. Select associated subcarrier spacing > coherence bandwidth.
     - ⇨ Enables maximum frequency diversity order.
- Result: system that avoids or mitigates problems encountered in SC DS-CDMA and MC-CDMA over wide range of delay spreads.

4.2 Advantages & Disadvantages

- **Advantages:**
  - ✓ **Independent fading on diversity-combined subcarriers.**
  - ✓ **Lower peak-to-average power ratio.**
  - ✓ **T-domain spreading codes remain orthogonal.**
    - ⇨ **Downlink at near single-user performance without MUD.**
  - ✓ **Frequency diversity order remains a constant value.**
- **Disadvantages:**
  - ✗ **Difference in Doppler shift destroys subcarrier orthogonality.**
    - ⇨ **Assertion: negligible at moderate traveling speeds.**
  - ✗ **Diversity order may be insufficient for BER target.**
    - ⇨ **Countermeasure: increase via transmit diversity.**

Multiple-access scheme	Number of subcarriers	Spreading gain	Number of resolvable paths	Diversity combining approaches
SC DS-CDMA	1	$\frac{T_b}{T_{c1}}$	$\left[\left\lfloor \frac{T_m}{T_{c1}} \right\rfloor + 1, \left\lfloor \frac{T_M}{T_{c1}} \right\rfloor + 1\right]$	RAKE
MC-CDMA	$\frac{2UT_b}{T_{c1}} - 1$	$\frac{2T_b}{T_{c1}}$	1	F-domain
MC DS-CDMA	$\frac{2T_c}{T_{c1}} - 1$	$\frac{T_s}{T_c}$	$\left[\left\lfloor \frac{T_m}{T_c} \right\rfloor + 1, \left\lfloor \frac{T_M}{T_c} \right\rfloor + 1\right]$	RAKE and/or F-domain

	Achievable diversity order	Slow fading	Strong ISI	Correlation between combined components
SC DS-CDMA	$\left[\left\lfloor \frac{T_m}{T_{c1}} \right\rfloor + 1, \left\lfloor \frac{T_M}{T_{c1}} \right\rfloor + 1\right]$	Yes, if $T_b < 1/(\Delta F)$	Yes, if $T_b < T_M$	No
MC-CDMA	$\left(\frac{2UT_b}{T_{c1}} - 1\right) \Big/ U$	Yes, if $T_s < 1/(\Delta F)$	Yes, if $UT_b < T_M$	Yes, if $\frac{U}{T_s} < \frac{1}{T_m}$, or if $(T_b > T_m)$
MC DS-CDMA	$\left[\left\lfloor \frac{T_m}{T_c} \right\rfloor + 1, \left\lfloor \frac{T_M}{T_c} \right\rfloor + 1\right] \times \left(\frac{2T_c}{T_{c1}} - 1\right) \Big/ U$	Yes, if $T_s < 1/\Delta F$	Yes, if $UT_b < T_M$	Yes, if $\frac{U}{T_c} < \frac{1}{T_m}$

T_{c1}: Chip duration of spreading codes in SC DS-CDMA; T_c: Chip duration of spreading codes in MC DS-CDMA; T_b: Bit duration of input information; T_s: Symbol duration; U: Number of bits involved in S-P conversion; T_m: Delay spread of the environment with the lowest delay spread; T_M: Delay spread of the environment with the highest delay spread; ΔF: Maximum Doppler frequency shift.

- MU-MC-CDMA
- RAKE RX
- OVSF DCA-SCHEDULING
- NOVSF