S-72.3320 Advanced Digital Communication (4 cr)

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- Lectures: Timo O. Korhonen, tel. 09 451 2351, Michael Hall, tel. 09 451 2343
- Course assistants: Seppo Saastamoinen (seppo.saastamoinen @hut.fi), tel. 09 451 5417, Naser Tarhuni (ntarhuni @pop.hut.fi), tel. 09 451 2255
- Study modules: Examination /Tutorials (voluntary) /Project work
- NOTE: Half of exam questions directly from tutorials
- Project work guidelines available at the course homepage

Practicalities

- References: (no need to buy these, supplementary material distributed later by Edita)
  - A. B. Carlson: Communication Systems (4th ed.)
  - J. G. Proakis, Digital Communications (4th ed.)
  - L. Ahlin, J. Zander: Principles of Wireless Communications
- Prerequisites: S-72.1140 Transmission Methods, (recommended S-72.1130 Telecommunication Systems)
- Homepage: http://www.comlab.hut.fi/studies/3320/
- Timetables:
  - Lectures: Tuesdays 12-14 S3, Fridays 10-12 S2
  - Tutorials: Fridays 14-16 S1

Timetable – spring 2006

- *27.1 Basics of Spread Spectrum Communications*
- *31.1 Fading Multipath Radio Channels*
- *3.2 no lecture*
- *7.2. Digital Transmission over a Fading Channel*
- *10.2 Cyclic Codes*
- *14.2 OFDM in Wideband Fading Channel*
- *17.2 Convolutional Codes*
- *21.2 Fiber-optic Communications*
- *24.2 Optical Networking*

S-72.3320 Advanced Digital Communication (4 cr)

Spread spectrum and

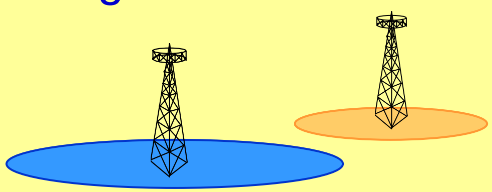
Code Division Multiple Access (CDMA) communications

Spread Spectrum (SS) Communications - Agenda Today

- 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
- Asynchronous CDMA systems

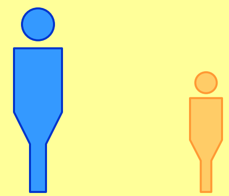
How Tele-operators* Market CDMA

Coverage



For Coverage, CDMA <u>saves wireless carriers</u> from deploying the 400% more cell site that are required by GSM

Capacity

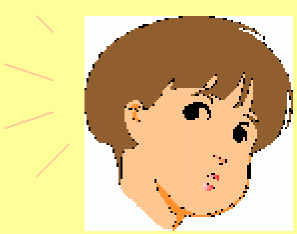


CDMA's capacity supports at least 400% <u>more revenue-producing subscribers</u> in the same spectrum when compared to GSM

Cost

A carrier who deploys CDMA instead of GSM will have <u>a lower capital cost</u>

Clarity



CDMA with PureVoice provides <u>wireline clarity</u>

Choice

CDMA offers the choice of <u>simultaneous</u> voice, async and packet data, FAX, and SMS.

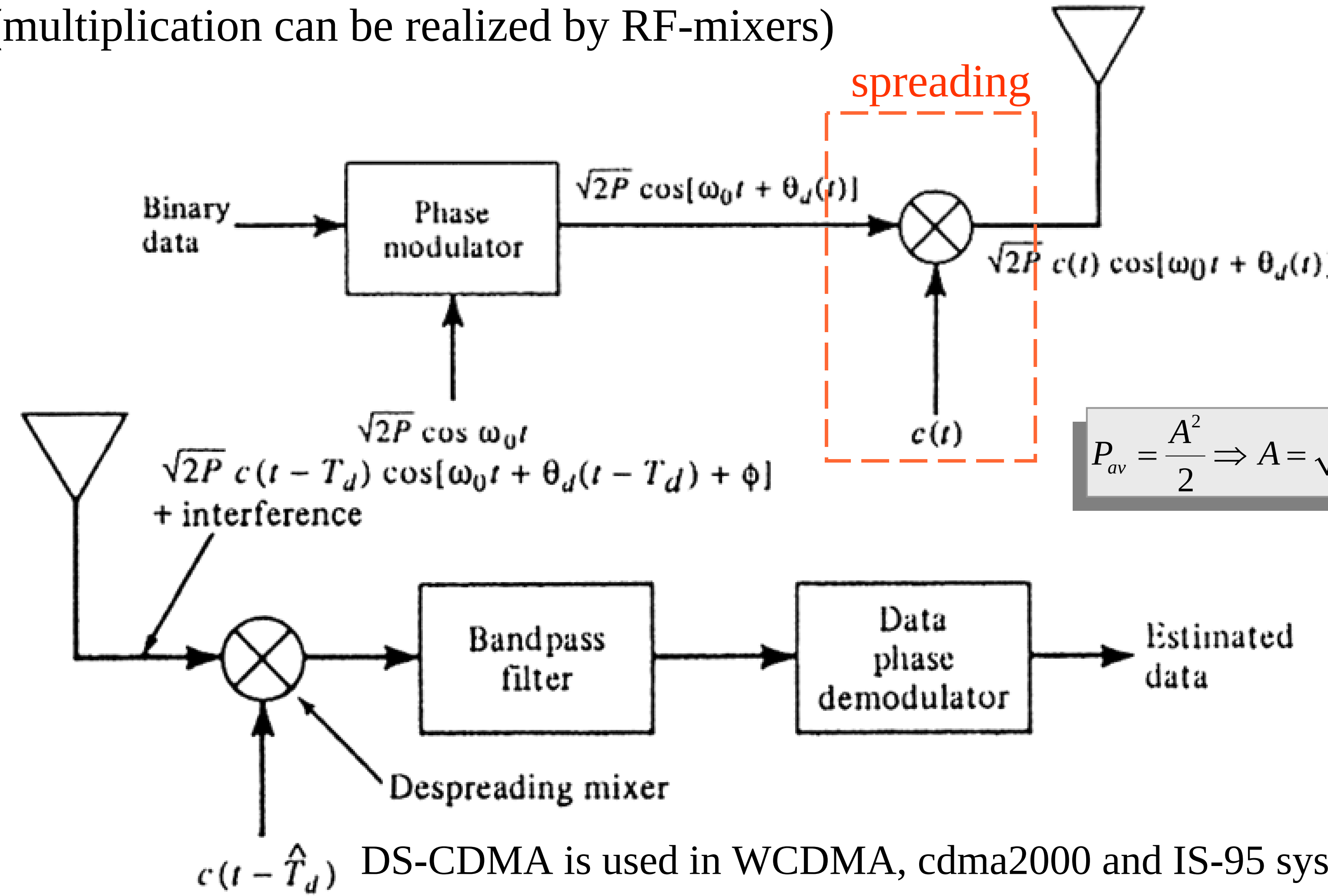
Customer satisfaction

The Most solid foundation for <u>attracting and retaining subscriber</u> is based on CDMA

**From Samsumg's narrowband CDMA (CDMAOne®) marketing (2001)*

Direct Sequence Spread Spectrum (DS-SS)

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

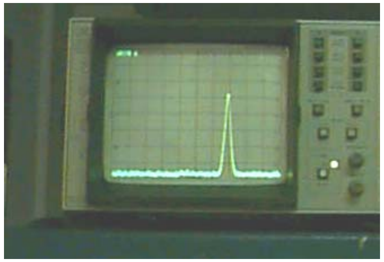


$$P_{av} = \frac{A^2}{2} \Rightarrow A = \sqrt{2P_{av}}$$

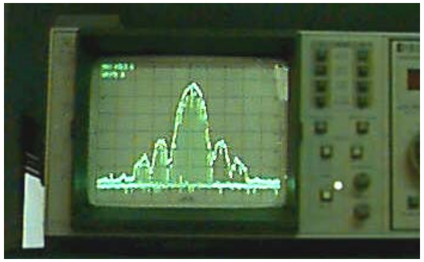
DS-CDMA is used in WCDMA, cdma2000 and IS-95 systems

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)

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:

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

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

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

$$\Rightarrow M_j = 18\,\text{dB}, \text{additional interference and noise can deteriorate}$$

$$\text{received SNR by this amount}$$

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:

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

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

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

$B_{RF,filt}$: bandwidth for polar mod.
M: number of levels
k: number of bits

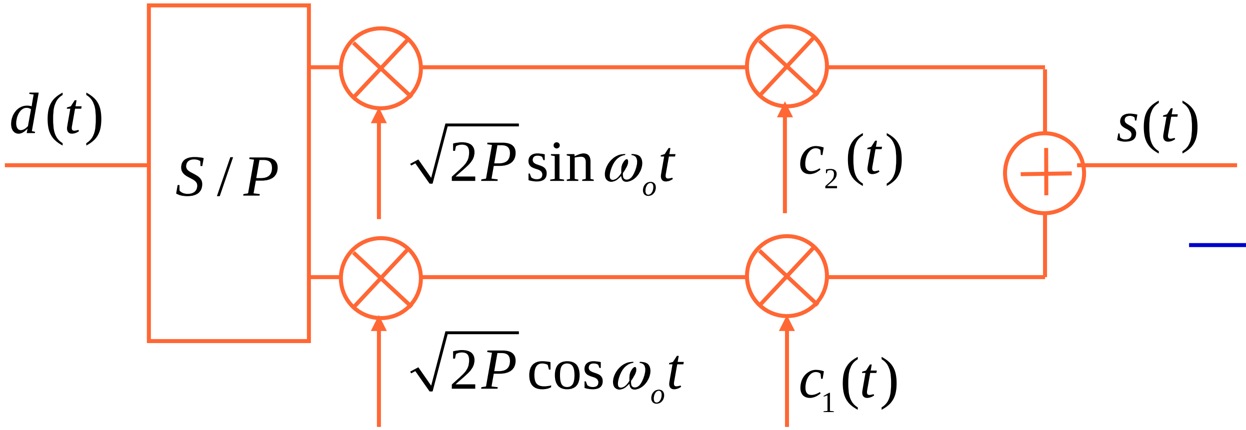
$$\left(M = 2^k \Rightarrow k = \log_2 M\right)$$

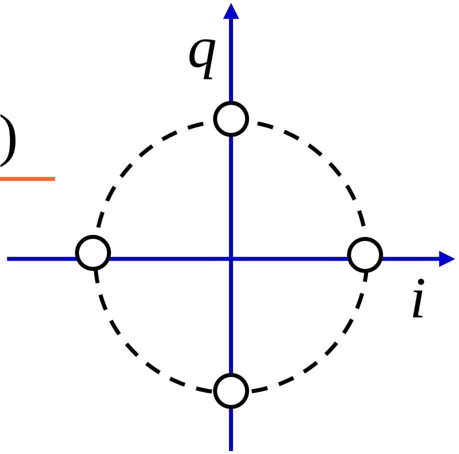
- Energy efficiency (reception sensitivity): The value of $\gamma_b = E_b / N_0$ to obtain a specified error rate (often 10^{-9}). For BPSK the error rate is

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

- 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





Constellation diagram

- 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

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

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

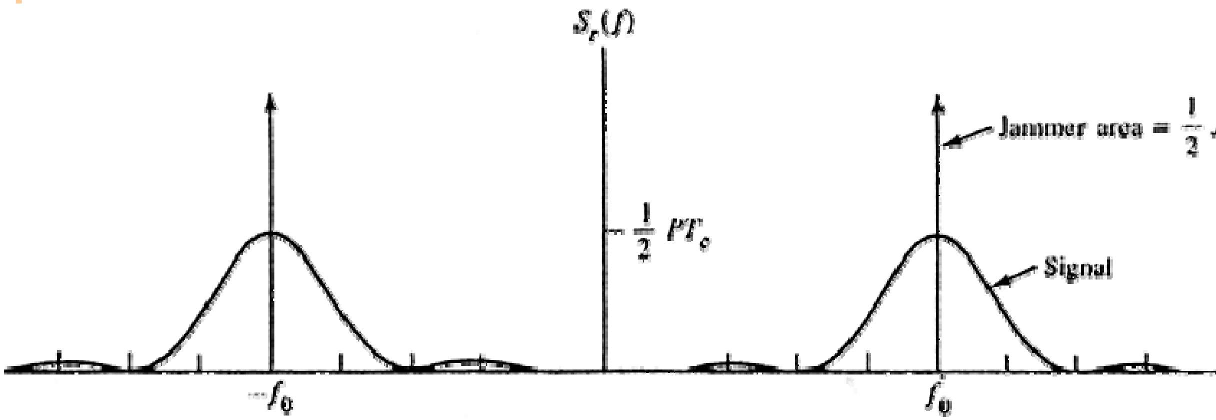
- The received signal and the local code are phase-aligned:

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

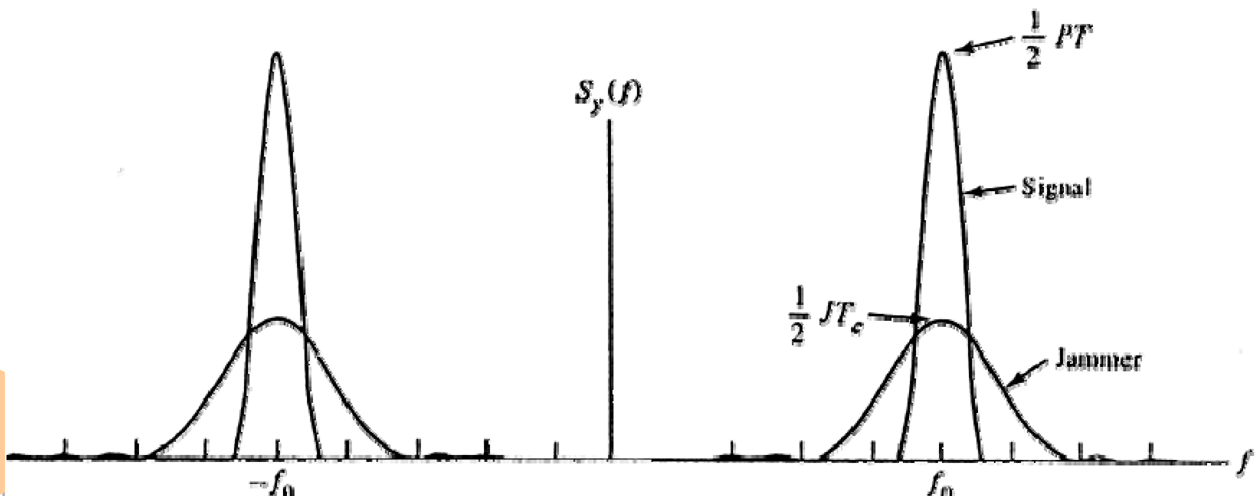
Data spectra after phase modulator

Tone Jamming (cont.)

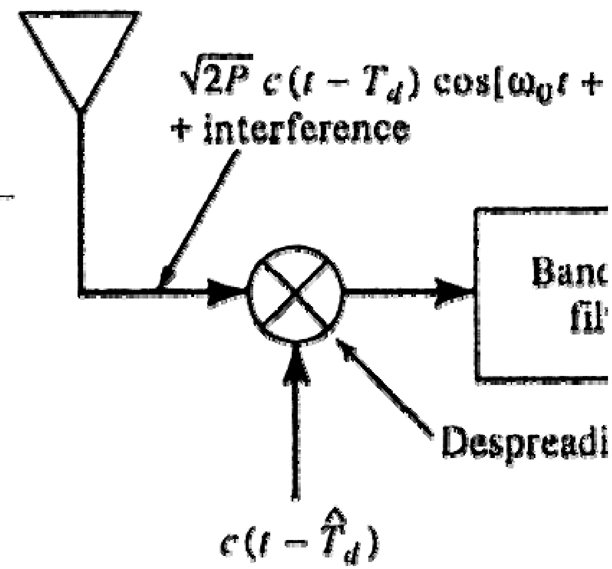
- Despreading spreads the jammer power and despreads the signal power:



(a) Before despreading

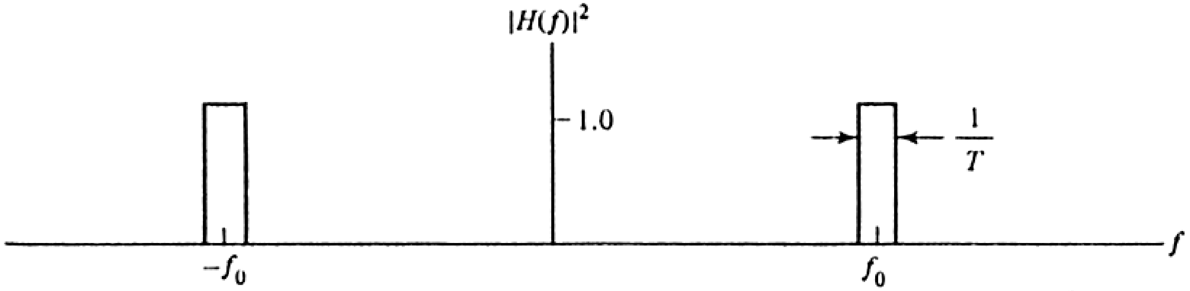


(b) After despreading

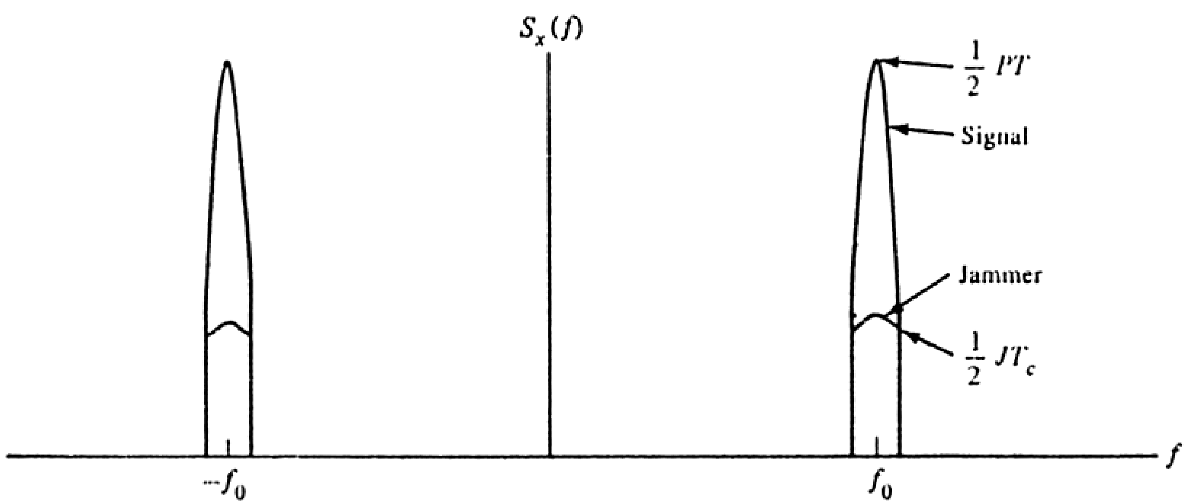


Tone Jamming (cont.)

- 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 code weight determines, from its own part, error rate
- 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

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

- 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, $d_{\min} = n$ (rep. coding)

*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* (repetition coding), thus $R_c w = (1/n)n = 1$ and

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

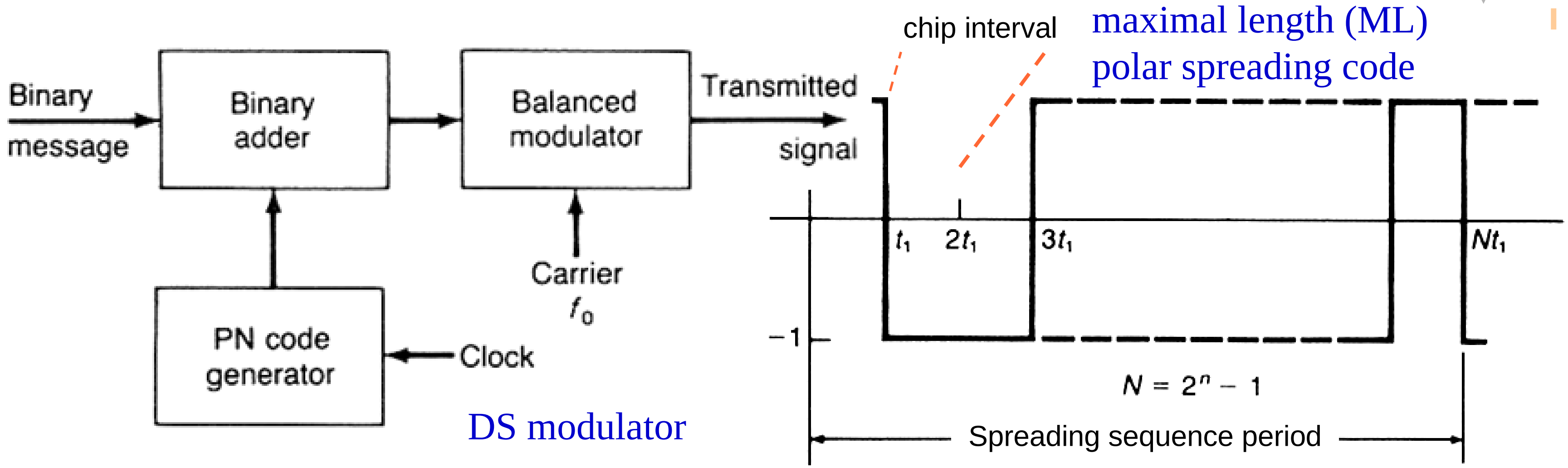
- We note that $E_b = P_{av}T_b = P_{av}/R_b$ and $N_0 = P_N/W$ [W/Hz] yielding

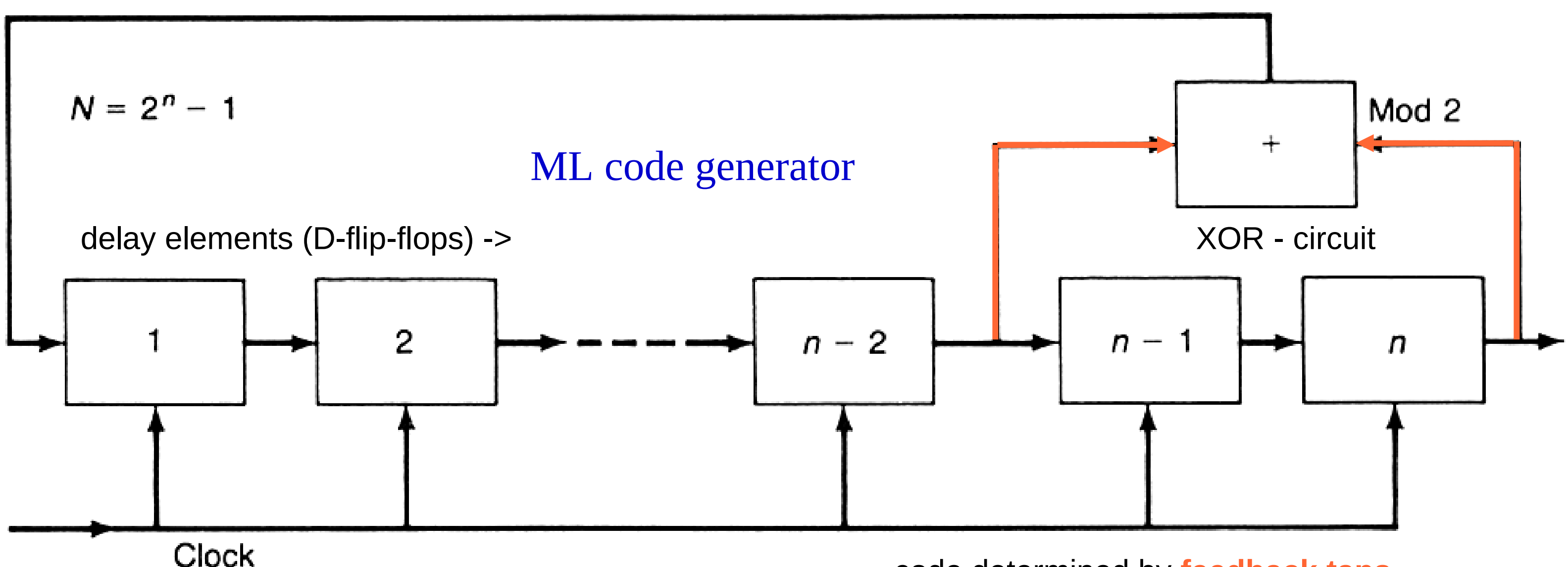
$$\frac{E_b}{N_0} = \frac{P_{av}/R}{P_N/W} = \frac{W/R}{P_N/P_{av}}$$

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

- Therefore, we note that by increasing system processing gain *W/R* or transmitted signal power P_{av}, error rate can be improved

Code Generation in DS-SS





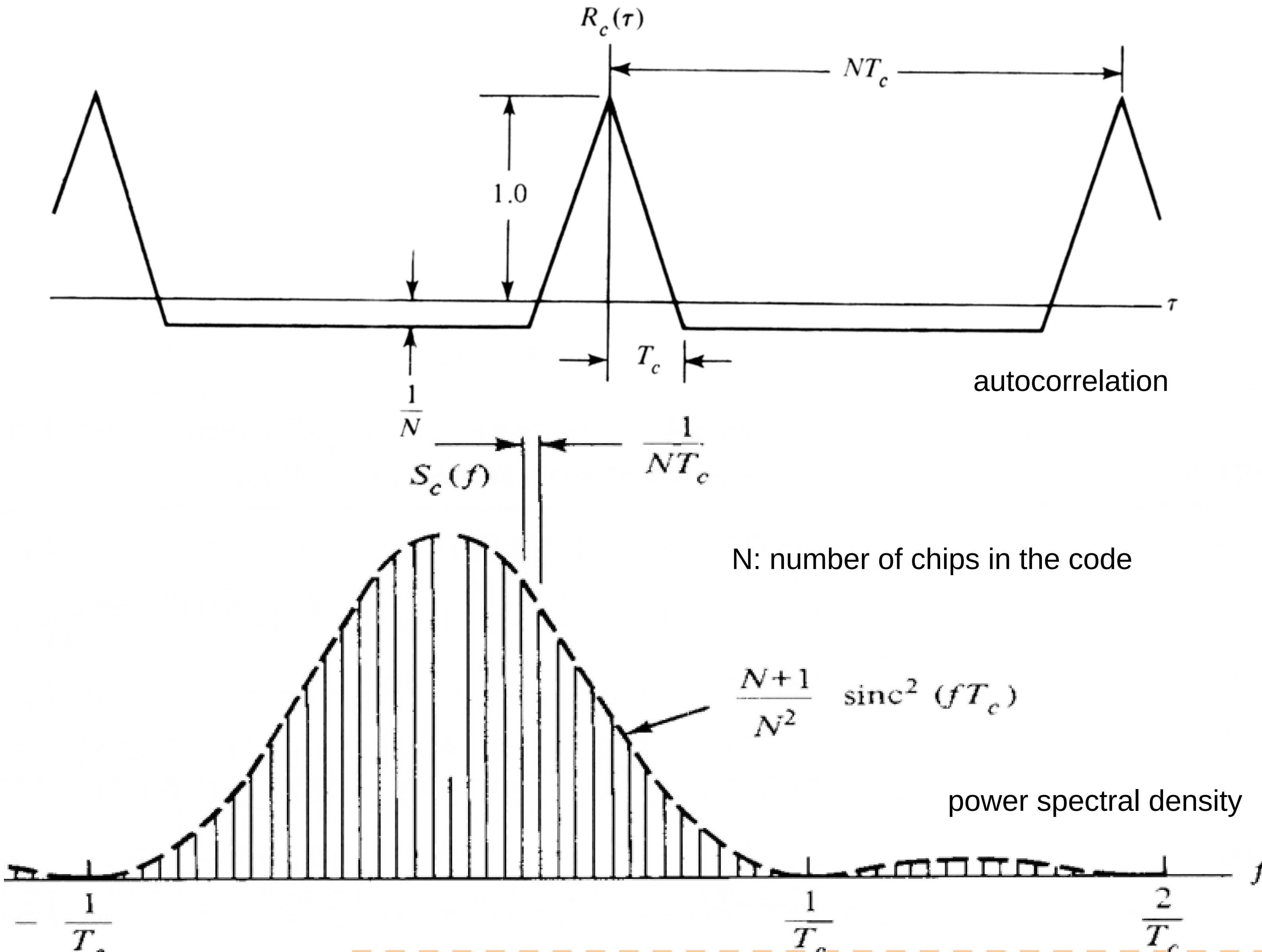
- code determined by **feedback taps**
- code rate determined by clock rate

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[1] of of maximal codes.
- **BCH-codes**. For every integer $m \geq 3$ there exists 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

1: Task: find out from net what is meant by dual codes!

Maximal Length Codes



autocorrelation

N: number of chips in the code

power spectral density

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)

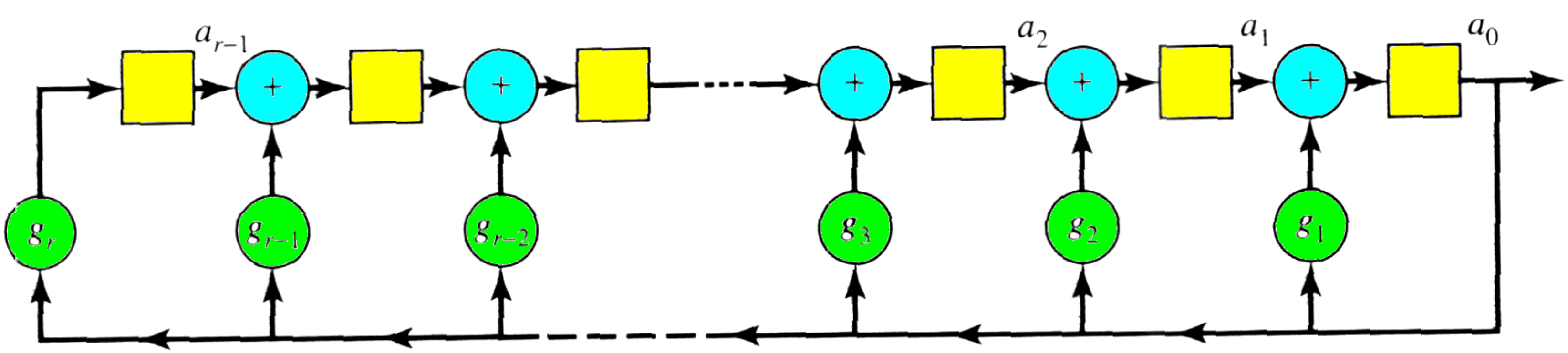
Degree	Octal Representation of Generator Polynomial (g_0 on right to g_r on left)
6	[103]*, [147], [155]
7	[211]*, [217], [235], [367], [277], [325], [203]*, [313], [345]
8	[435], [551], [747], [453], [545], [537], [703], [543]
9	[1021]*, [1131], [1461], [1423], [1055], [1167], [1541], [1333], [1605], [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

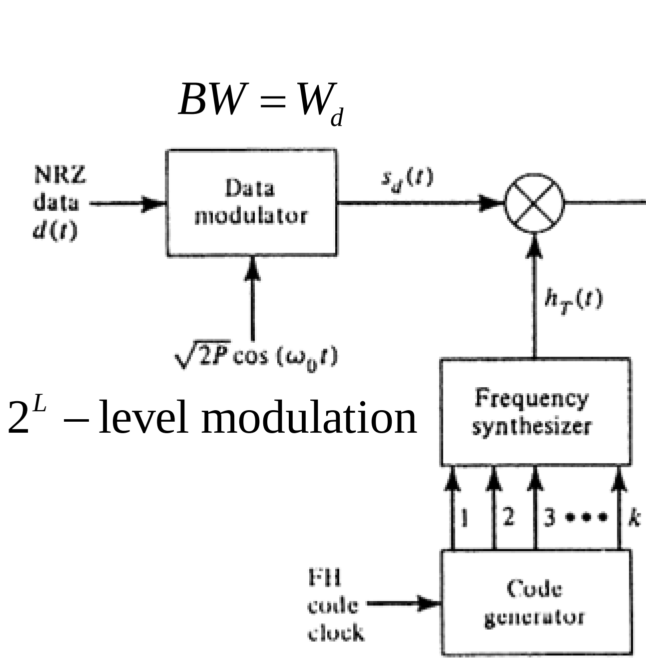
$$N = 2^n - 1 \text{ and } t(n) = \begin{cases} 1 + 2^{(n+1)/2}, \text{for } n \text{ odd} \\ 1 + 2^{(n+2)/2}, \text{for } n \text{ even} \end{cases}$$

(n: number of stages in the shift register)

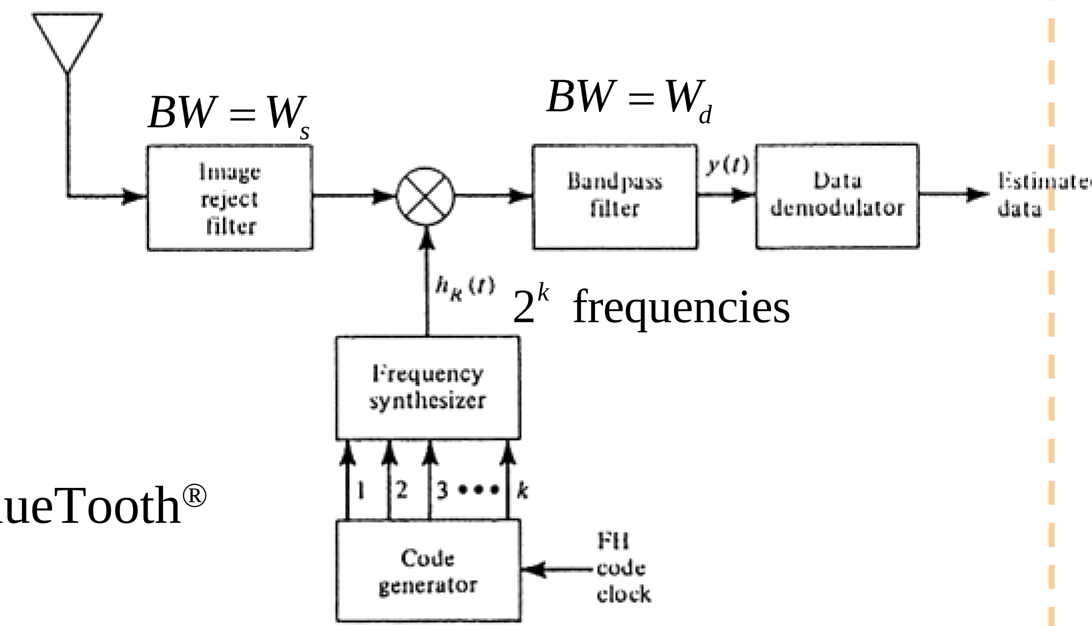
- Walsh and Gold codes are used especially in multiple access systems
- Gold codes are used in *asynchronous communications* because their crosscorrelation is quite good as formulated above

Frequency Hopping Transmitter and Receiver

- In FH-SS hopping frequencies are determined by the code and the message (bits) are usually non-coherently FSK-modulated



(a) Transmitter

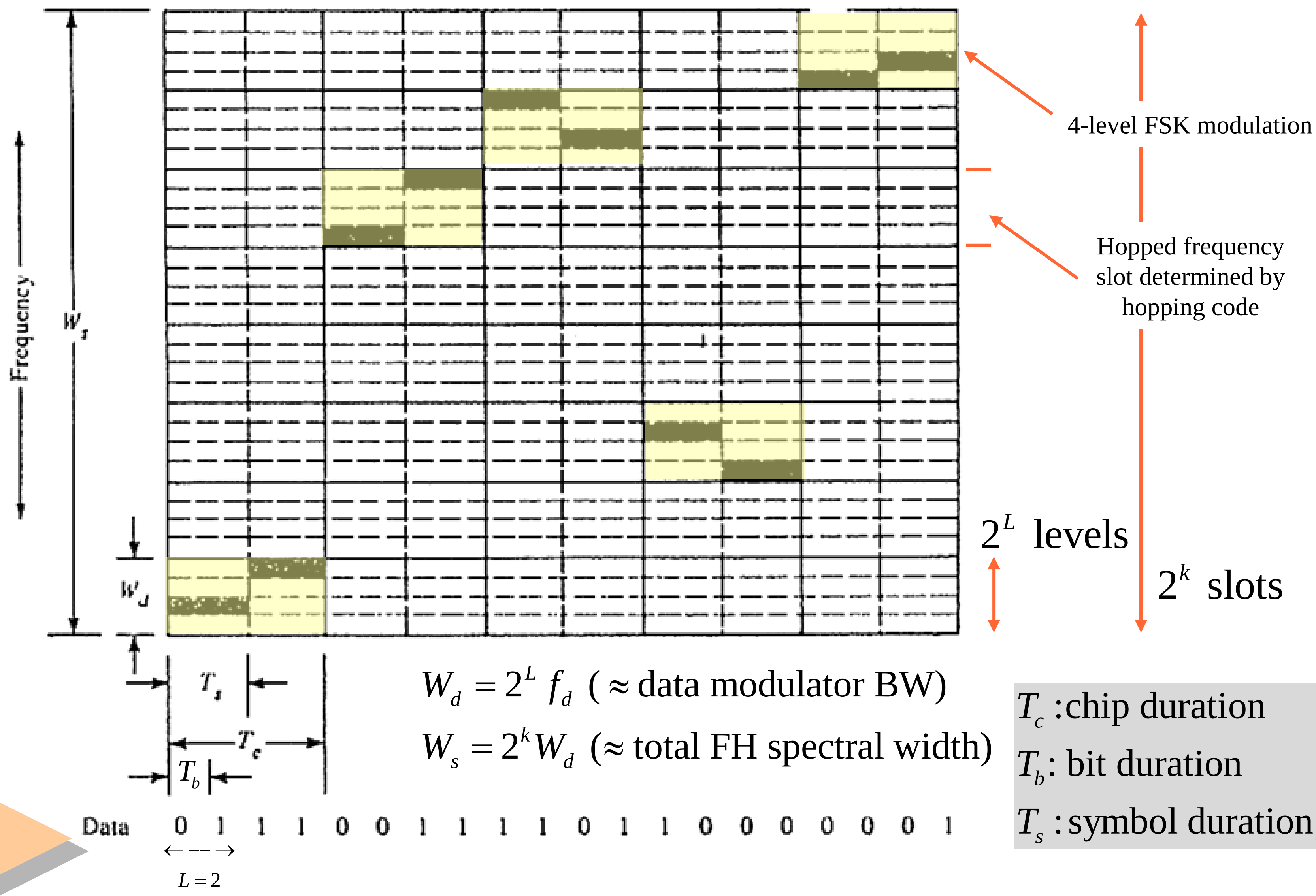


(b) Receiver

- This method is applied in BlueTooth®

Frequency Hopping Spread Spectrum (FH-SS)

(example: transmission of two symbols/chip)



$W_d = 2^L f_d$ (≈ data modulator BW)

$W_s = 2^k W_d$ (≈ total FH spectral width)

T_c :chip duration

T_b: bit duration

T_s :symbol duration

Error Rate in Frequency Hopping

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

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

and the respective symbol error rate is (hard-decisions)

$$P_{es} = \tfrac{1}{2}\exp\left(-\gamma_b R_c/2\right), R_c = k/n < 1$$

- 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)

$$P_e = \exp\left(-\gamma_b/2\right)\underbrace{\frac{1}{2^{2L-1}}\sum_{i=0}^{L-1} K_i\left(\gamma_b/2\right)^i}_{\text{diversity gain - component}}, \gamma_b = L\gamma_c = LR_cE_b/N_0$$

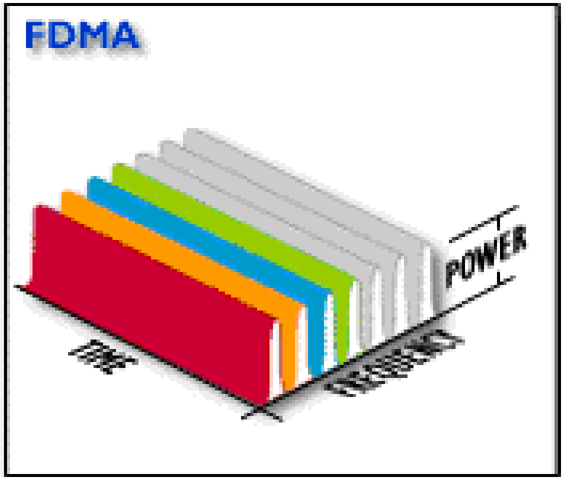
$$K_i = \frac{1}{i!}\sum_{r=0}^{L-1-i}\binom{2L-1}{\gamma}$$

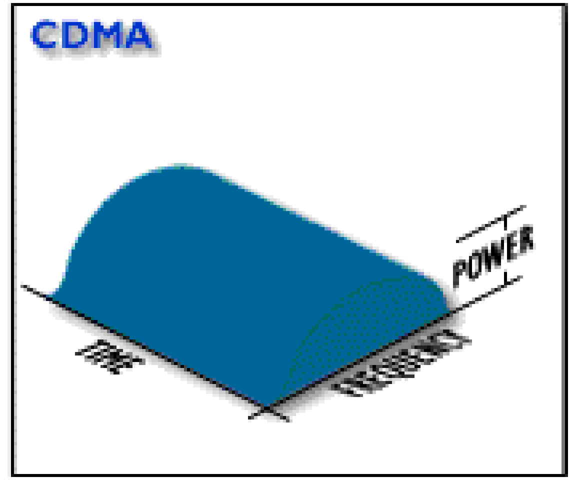
(For further details, see J.G.Proakis: Digital Communications (IV Ed), Section 13.3)

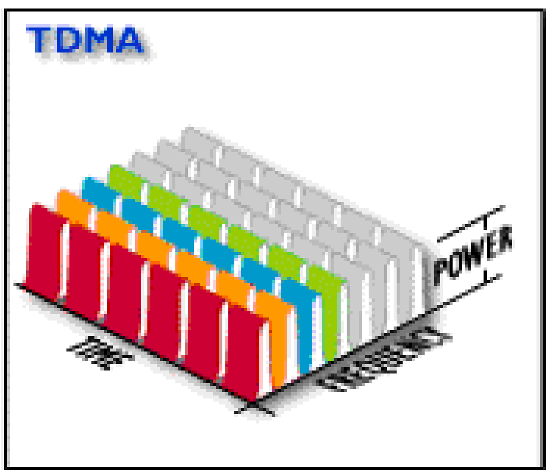
DS and FH compared

- FH is applicable in environments where there exist **tone jammers** that can be overcame by avoiding hopping on those frequencies
- DS is applicable for *multiple access* because it allows *statistical multiplexing* (**resource reallocation)** to other users (power control)
- FH applies usually **non-coherent modulation** due to carrier synchronization difficulties -> modulation method degrades performance
- Both methods were first used in *military communications*, $L_c \rightarrow 10^2 ... 10^7$
  - FH can be advantageous because the **hopping span** can be very large (makes *eavesdropping* difficult)
  - DS can be advantageous because **spectral density** can be much smaller than background noise density (transmission is unnoticed)
- FH is an **avoidance system**: does not suffer *near-far effect*!
- By using **hybrid systems** some benefits can be combined: The system can have a low probability of interception and negligible near-far effect at the same time. (*Differentially coherent modulation* is applicable)

Multiple access: FDMA, TDMA and CDMA





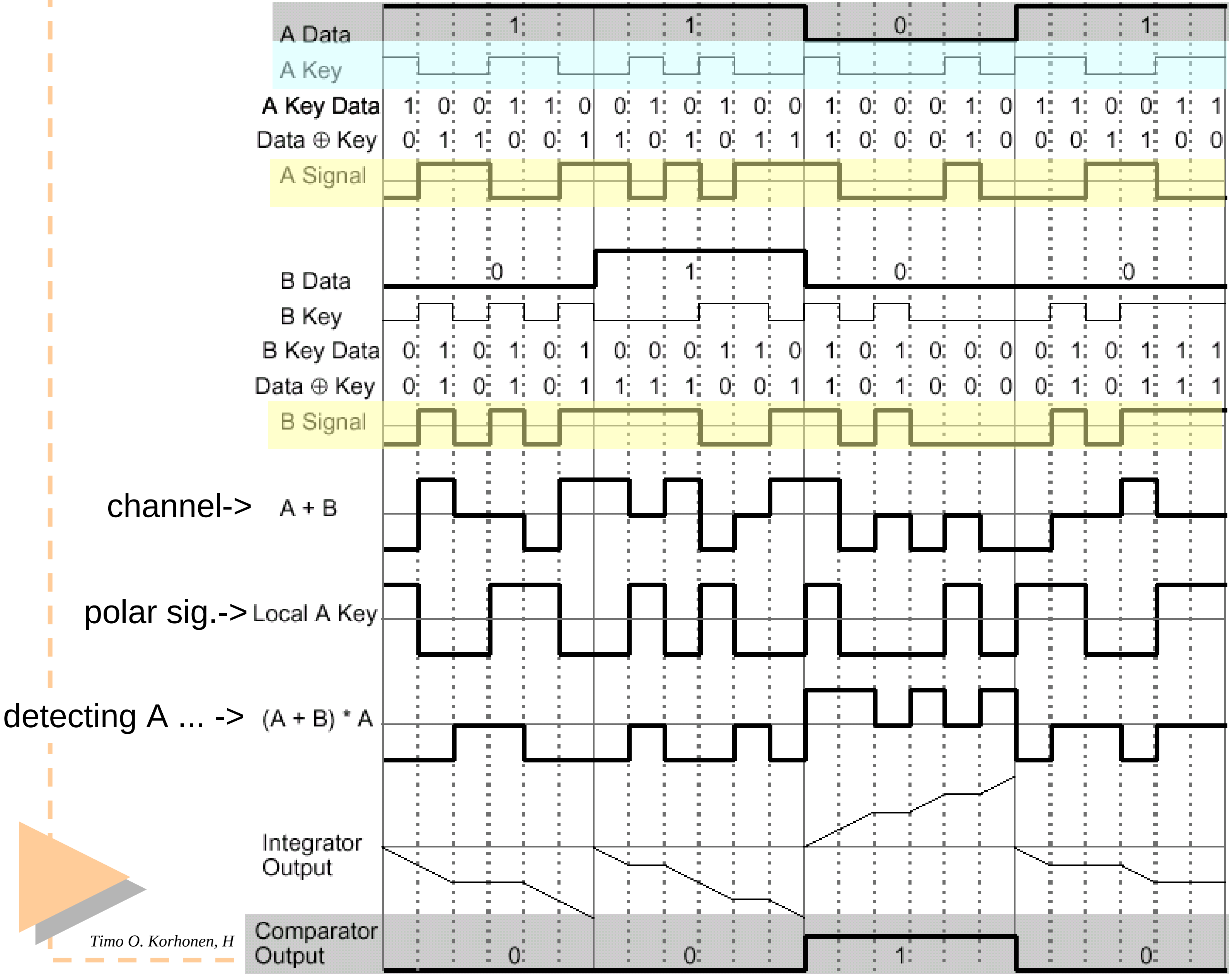


- FDMA, TDMA and CDMA yield conceptually the same capacity
- However, in wireless communications CDMA has improved capacity due to
  - statistical multiplexing
  - graceful degradation
- Performance can still be improved by adaptive antennas, multiuser detection, FEC, and multi-rate encoding

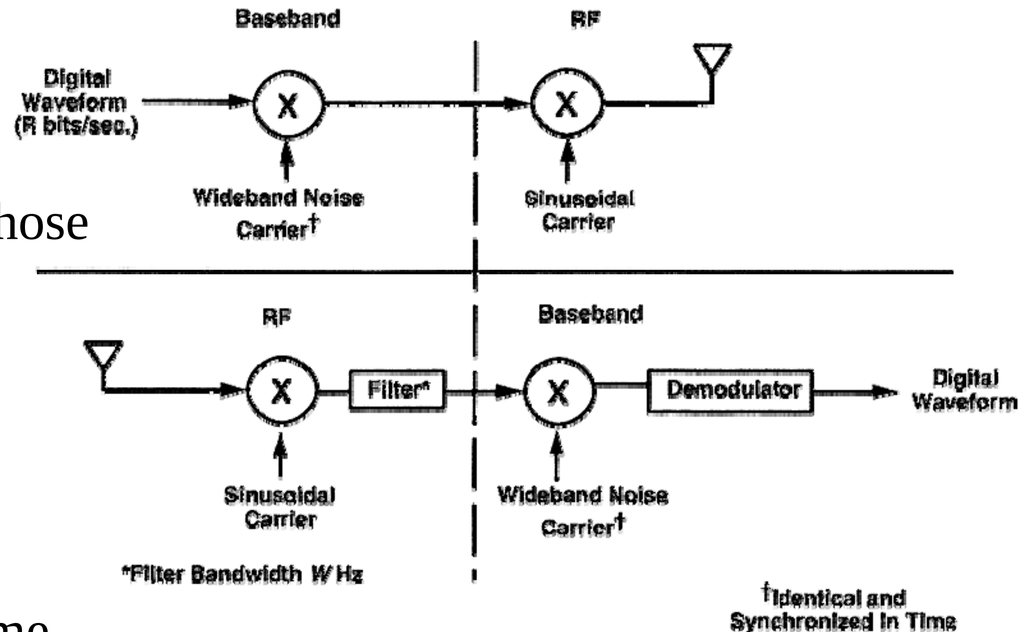
FDMA, TDMA and CDMA compared

- 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 difficult to apply in multipath channels that destroy code orthogonality
  - Therefore, in wireless CDMA-systems as in IS-95,cdma2000, WCDMA and IEEE 802.11 users 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

Example of DS multiple access waveforms



Capacity of a cellular CDMA system



- Consider uplink (MS->BS)
- Each user transmits Gaussian noise (SS-signal) whose deterministic characteristics are stored in RX and TX
- Reception and transmission are simple multiplications
- Perfect power control: each user's power at the BS the same
- Each user receives multiple copies of power P_r that is other user's interference power, therefore each user receives the interference power

$$I_k = (U - 1)P_r \qquad (1)$$

where U is the number of equal power users

Capacity of a cellular CDMA system (cont.)

- Each user applies a demodulator/decoder characterized by a certain *reception sensitivity* E_b/I_o (3 - 9 dB depending on channel coding, channel, modulation method etc.)
- Each user is exposed to the interference power density (assumed to be produced by other users only) $I_0 = I_k / B_T$ [W/Hz] (2)
  where B_T is the spreading (and RX) bandwidth
- Received signal energy / bit at the signaling rate R is

$$E_b = P_r / R \qquad [J]=[W][s] \quad (3)$$

- Combining (1)-(3) yields the number of users

$$I_k = (U-1)P_r \Rightarrow \; U-1 = \frac{I_k}{P_r} = \frac{I_o B_T}{E_b R} = \frac{(1/R)B_T}{E_b(1/I_0)} = \boxed{\frac{W/R}{E_b/I_0}} \quad (4)$$

- This can still be increased by using voice activity coefficient $G_v = 2.67$ (only about 37% of speech time effectively used), directional antennas, for instance for a 3-way antenna $G_A = 2.5$.

Capacity of a cellular CDMA system (cont.)

- In cellular system neighboring cells introduce interference that decreases capacity. It has been found out experimentally that this reduces the number of users by the factor

$$1+f \approx 1.6$$

- Hence asynchronous CDMA system capacity can be approximated by

$$U = \frac{W/R}{E_b/I_o}\frac{G_v G_A}{1+f}$$

yielding with the given values G_v=2.67, G_A=2.4, 1+f = 1.6,

$$U = \frac{4W/R}{E_b/I_o}$$

- Assuming efficient error correction algorithms, dual diversity antennas, and RAKE receiver, it is possible to obtain E_b/I_o=6 dB = 4, and then

$$U \approx \frac{W}{R}$$

This is of order of magnitude larger value than with the conventional (GSM;TDMA) systems!

Lessons Learned

- You understand what is meant by code gain, jamming margin, and spectral efficiency and what is their meaning in SS systems
- You understand how spreading and despreading works
- You understand the basic principles of DS and FH systems and know their error rates by using BPSK and FSK modulations (if required, formulas will be given in exam)
- You know the bases of code selection for SS system. (What kind of codes can be applied in SS systems and when they should be applied.)
- You understand how the capacity of asynchronous CDMA system can be determined