Digital Communication Systems

Spread spectrum and

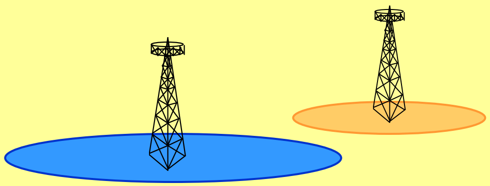
Code Division Multiple Access (CDMA) communications

Spread Spectrum 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

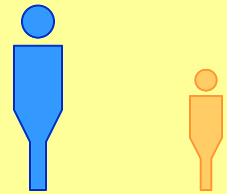
How Tele-operators* Market CDMA

Coverage



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

Capacity

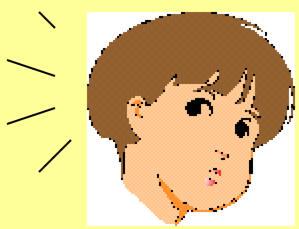


CDMA's capacity supports at least 400% <u>more revenue-producing subscribers</u> in the same spectrum when compared to GSM

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.

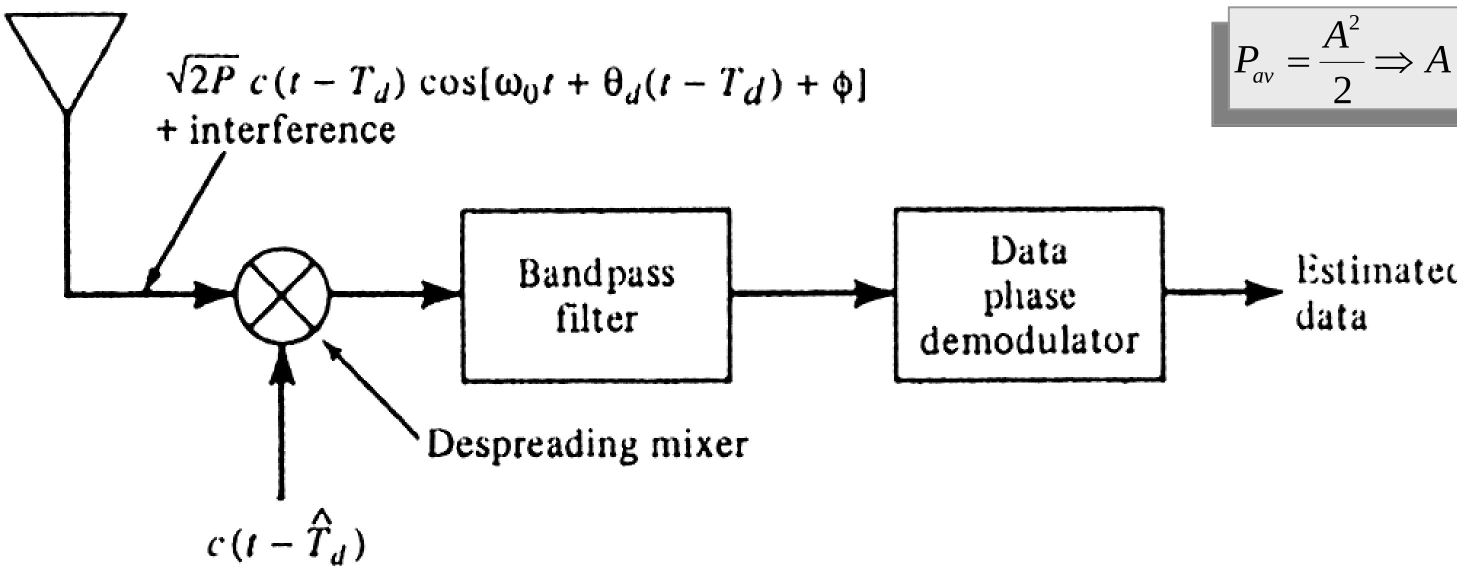
Customer satisfaction

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

Direct Sequence Spread Spectrum (DS-SS)

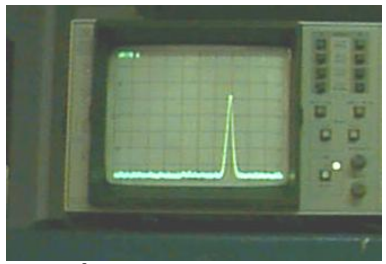
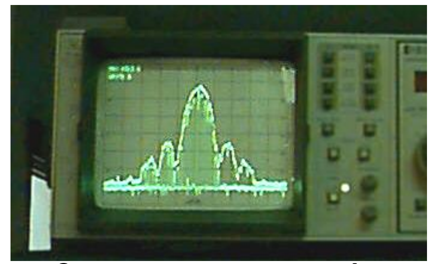
- This figure shows BPSK-DS transmitter [spreading] and receiver
  (multiplication can be realized by RF-mixers)

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



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

- Interference and noise immunity of SS system is larger, the larger the processing gain
- 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
  - 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
  - Tells nois haza

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

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

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

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

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

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:

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

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

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

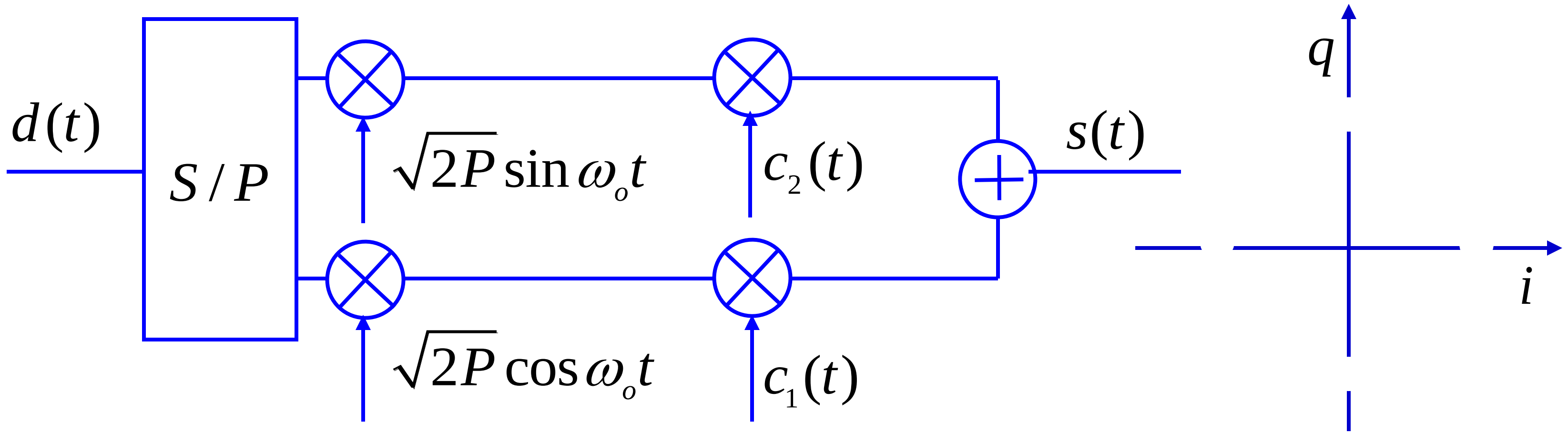
$$\left(M = 2^k \Rightarrow k = \log_2 M\right)$$

- 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

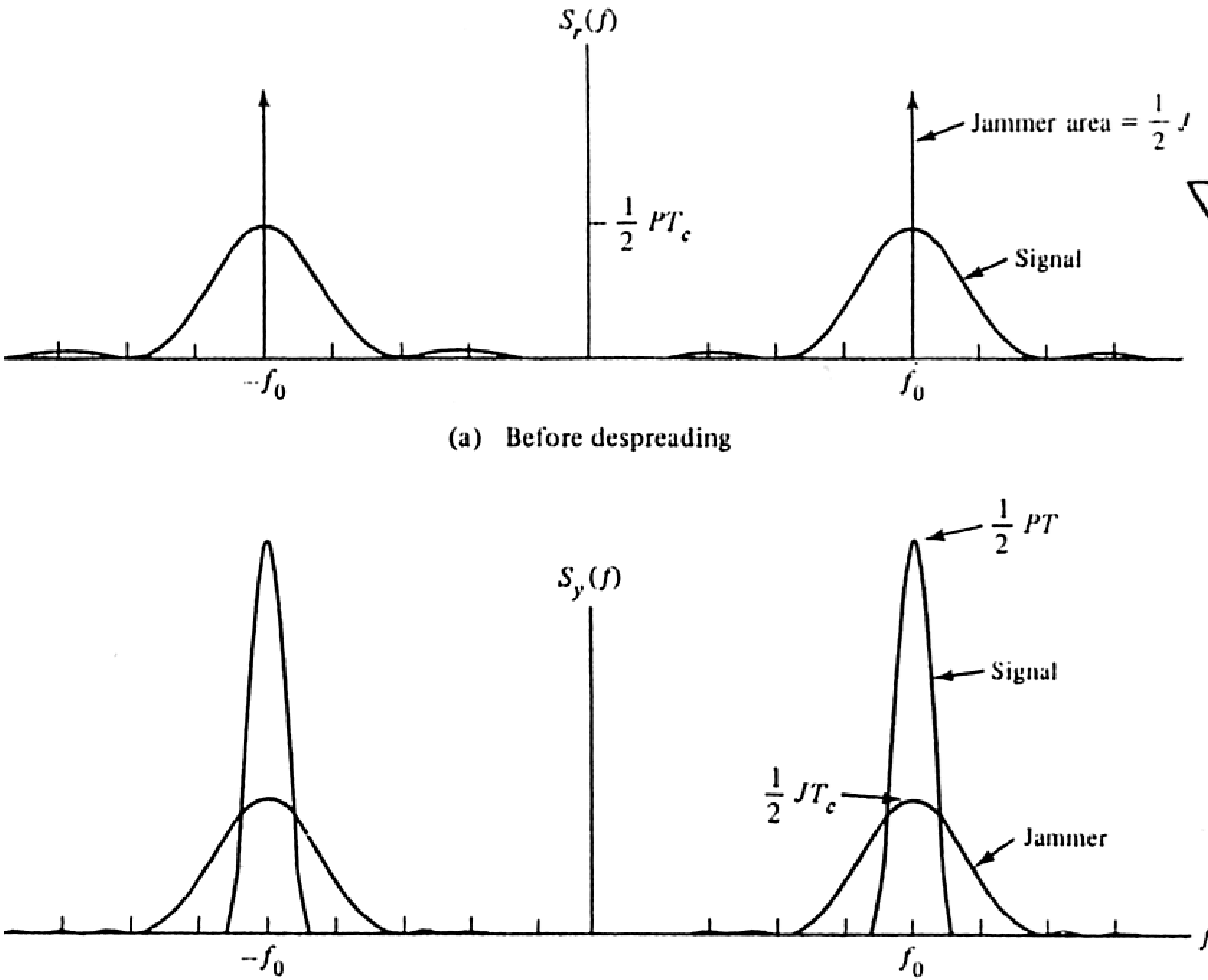


- After serial-parallel conversion (S/P) data modulates the orthogonal carriers
- Modulation on orthogonal carriers spreaded by codes c_1 and c_2
- Spreading codes c_1 and c_2 may or may not be orthogonal (System performance is independent of their orthogonality, why?)
- What kind of circuit can make 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
- The respective PSD of the received chip-rate signal is
- At the receiver *r(t)* is multiplied with the local code *c(t)* (=*despreading*)

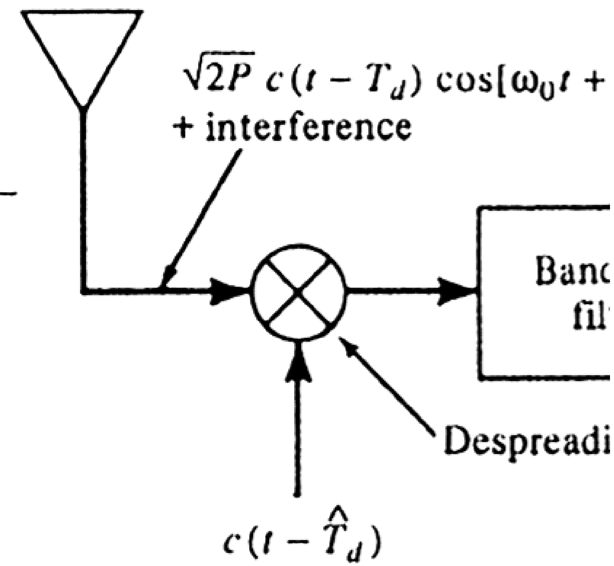
Tone Jamming (cont.)



(a) Before despreading

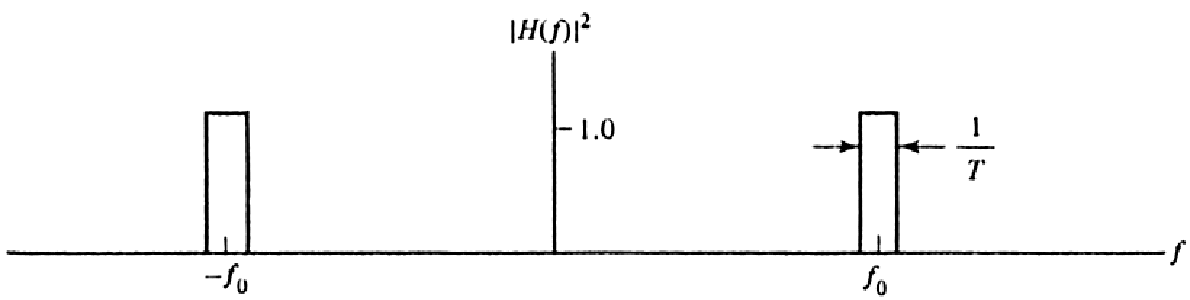
(b) After despreading

power and

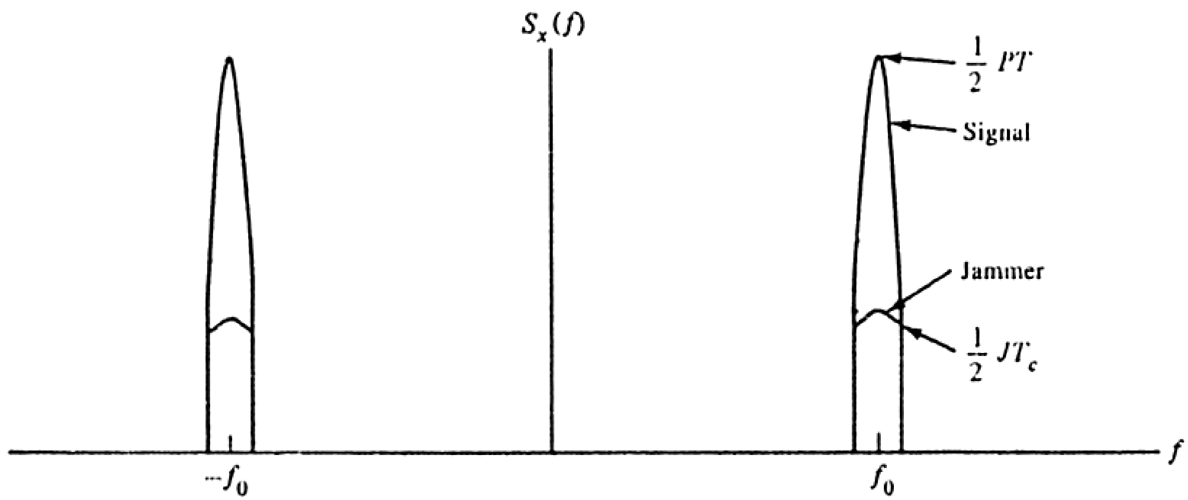


Tone Jamming (cont.)

- Filte … lator)
  afte … ıer
  pow …



(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

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

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

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

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

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

Example: Error Rate of Uncoded Binary BPSK-DS

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

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

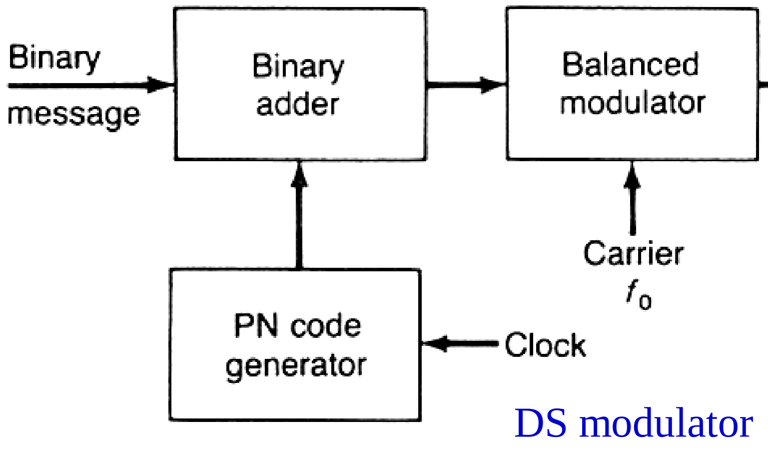
- We note that $E_b = P_{av} T_b = P_{av} / R_b$ and $J_0 = J_{av} / W$ yielding

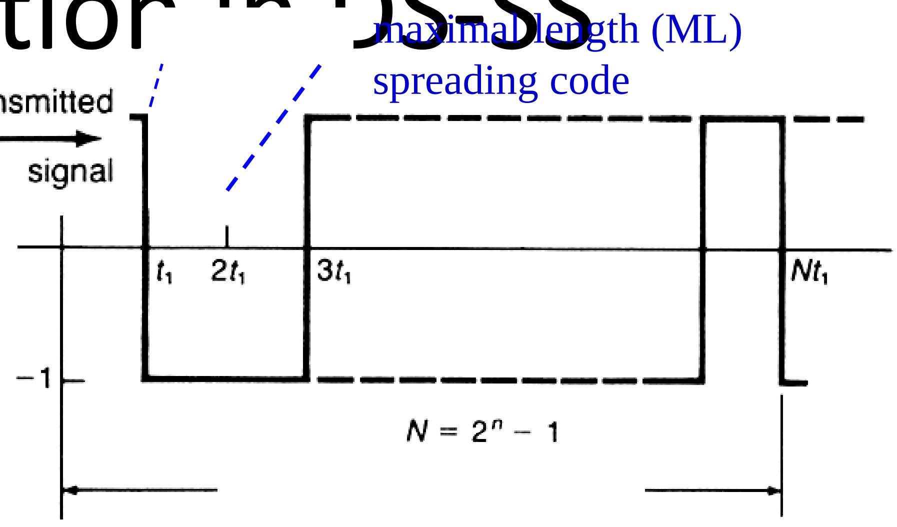
$$\frac{E_b}{J_0} = \frac{P_{av} / R}{J_{av} / W} = \frac{W / R}{J_{av} / P_{av}}$$

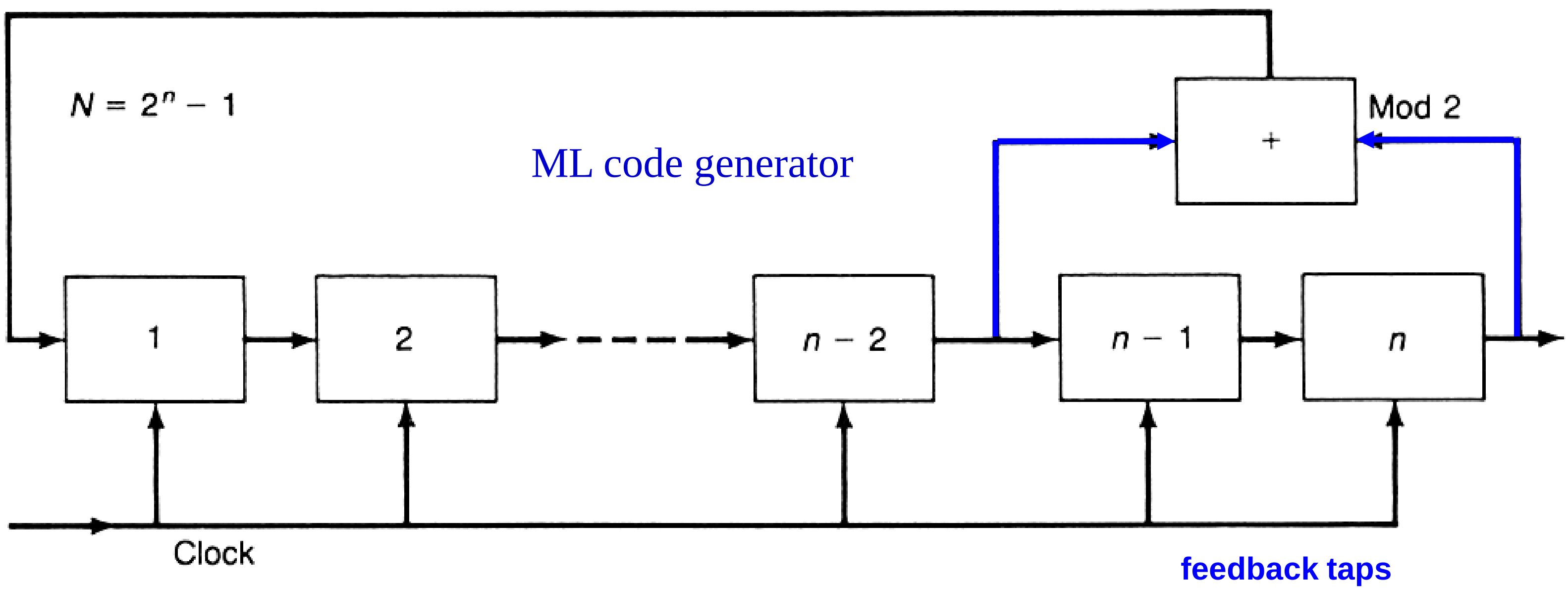
$$\Rightarrow P_e = Q\left(\sqrt{\frac{2W / R}{J_{av} / P_{av}}}\right)$$

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

Code Generation in DS-SS



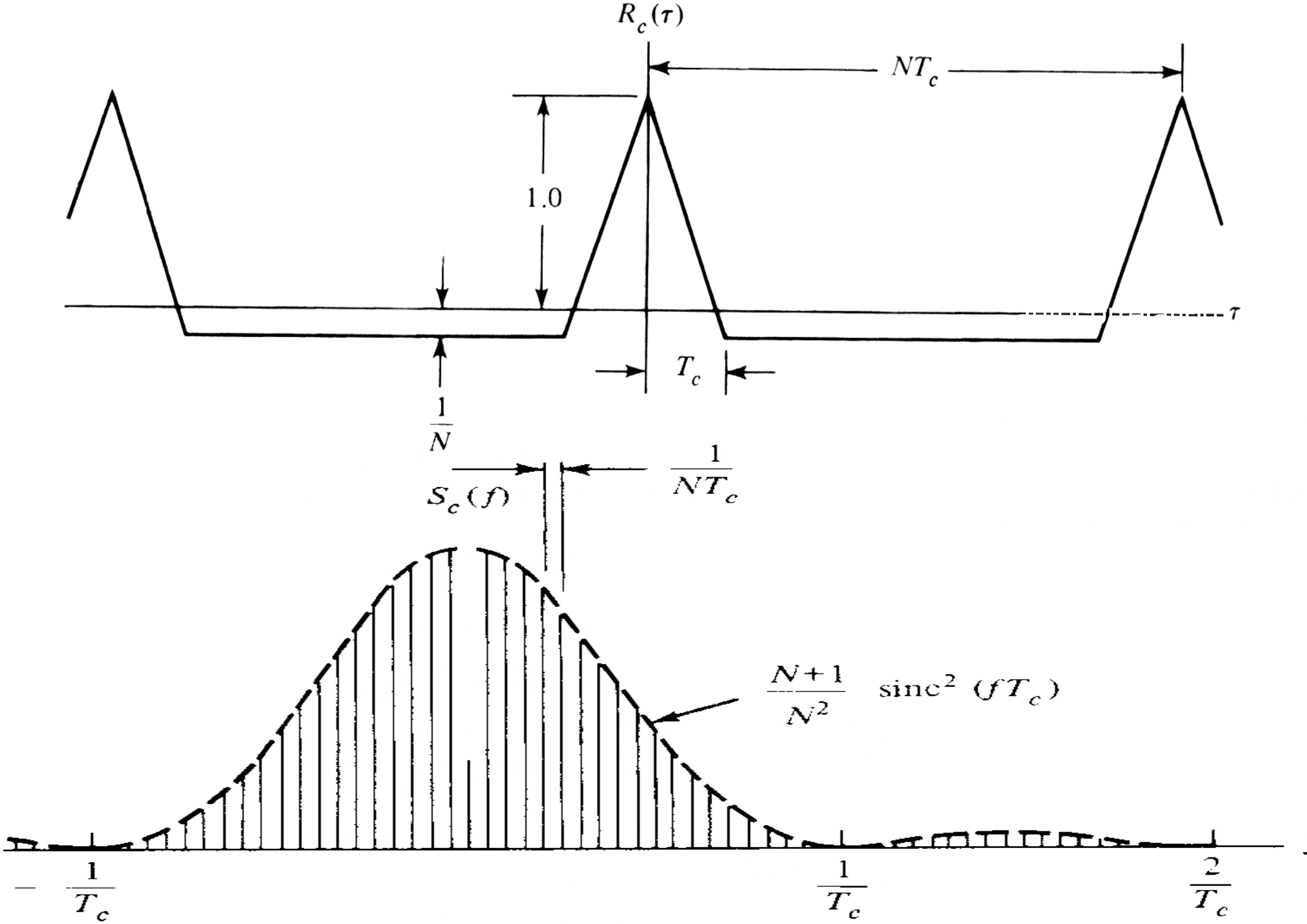




Some Cyclic Block Codes

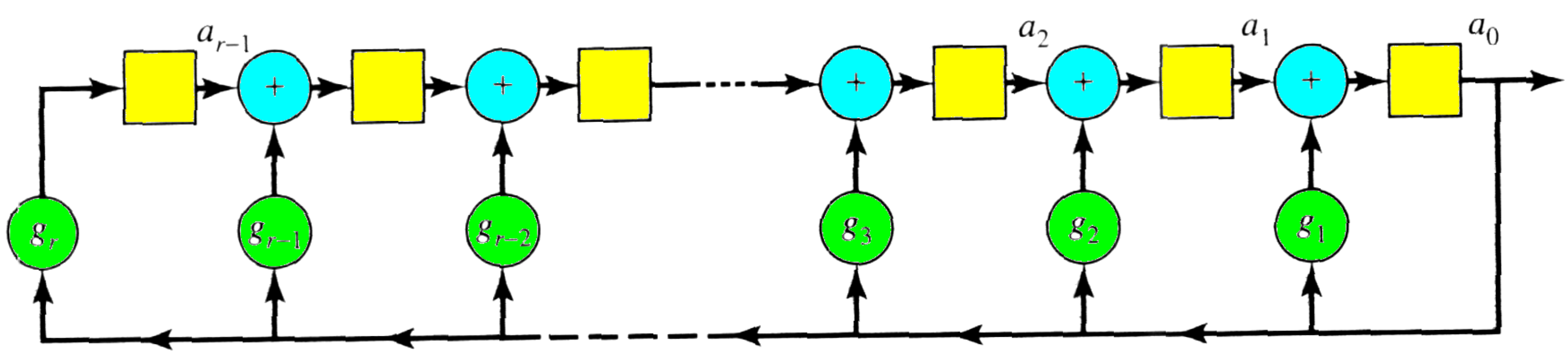
- (n,1) **Repetition codes**. High coding gain, but low rate
- (n,k) **Hamming codes**. Minimum distance always 3. Thus can detect 2 errors and correct one error. $n=2^m-1, k = n - m,$
- **Maximum-length codes**. For every integer there exists a maximum length code (n,k) with $n = 2^k - 1, d_{min} = 2^{k-1}$. Hamming codes are dual[1] of of maximal codes.
- **BCH-codes**. For every integer there exist a code with $n = 2^m-1,$ and 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 and
- Nowadays BCH and RS are very popular due to <u>large d_{min}, large number of codes, and easy generation</u>
- For further code references have a look on self-study material!

Maximal Length Codes



Design of Maximal Length Generators by a Table Entry

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



Other Spreading Codes

- Walsh codes: Orthogonal, used in *synchronous systems*, also in WCDMA downlink
- Generation recursively: $H_0 = [0] \quad H_n = \begin{bmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & \overline{H_{n-1}} \end{bmatrix}$

$$H_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

- All rows and columns of the matrix are orthogonal:

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

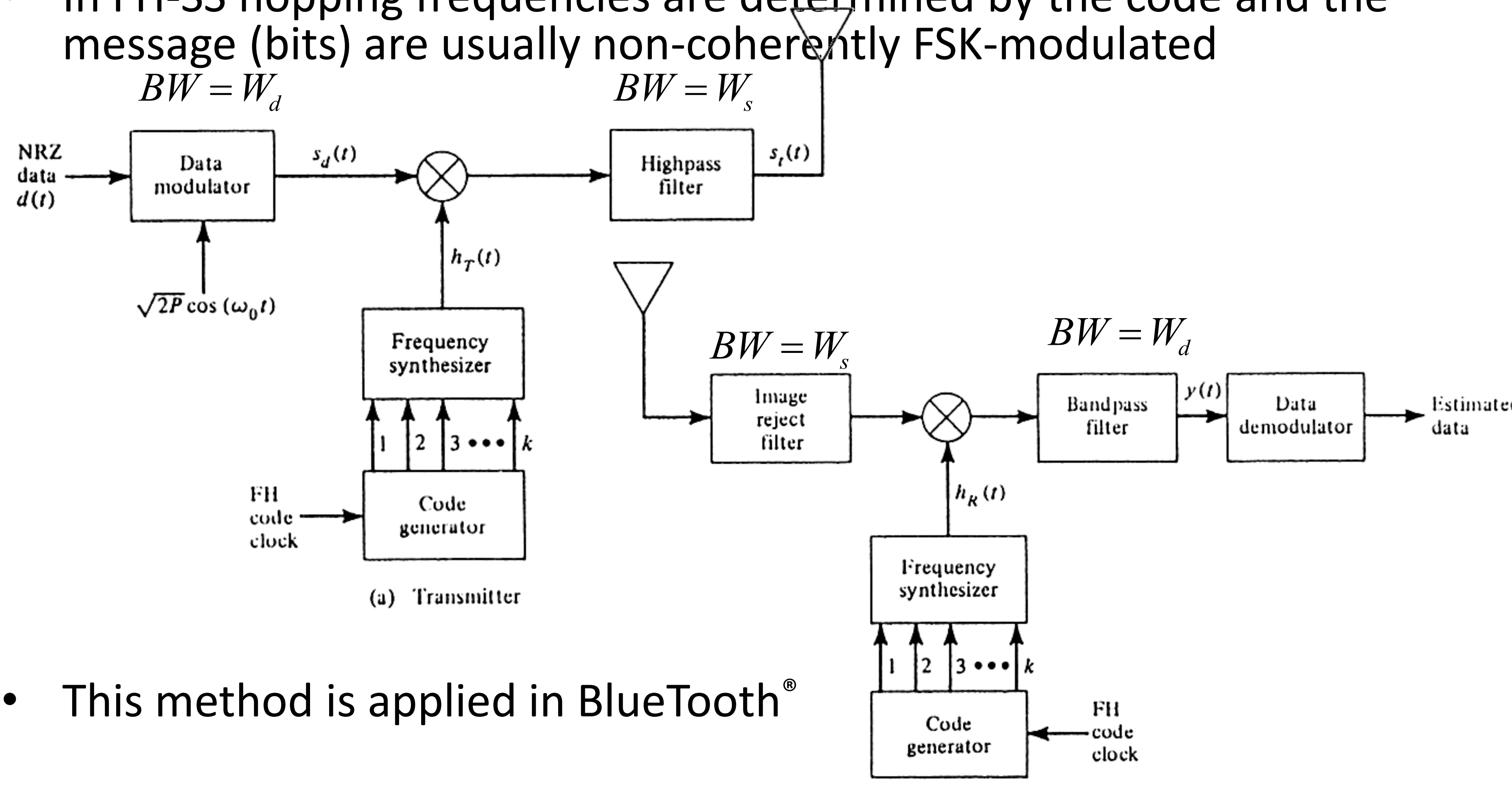
- Gold codes: Generated by summing *preferred pairs* of maximal length codes. Have a guarantee 3-level crosscorrelation: $\{-t(n)/N, 1/N, (t(n)-2)/N\}$
- For *N*-length code there exists *N* + 2 codes in a code family and

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

- 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 Transmitter and Receiver

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



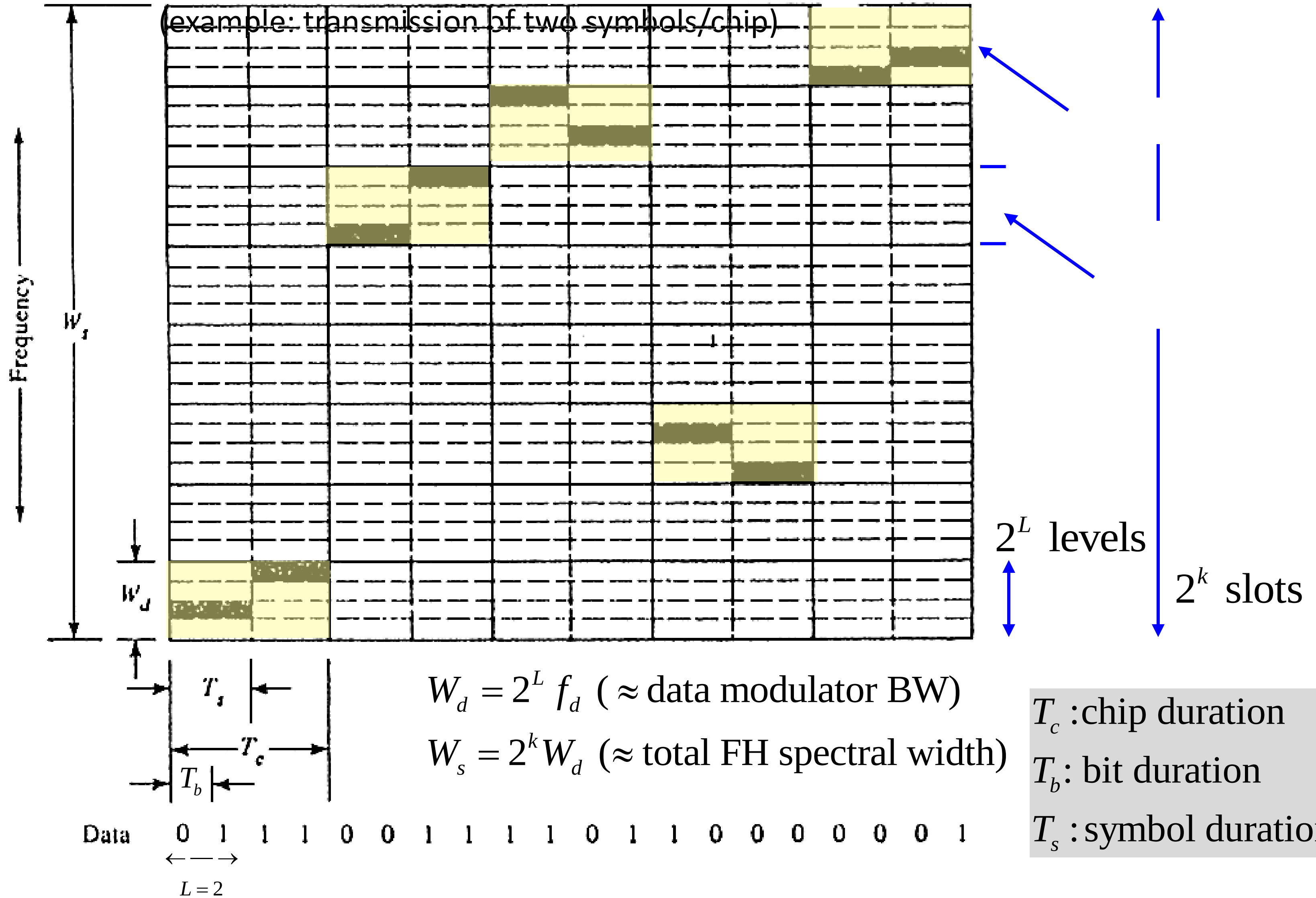
(a) Transmitter

(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 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
$$P_e = \frac{1}{2}\exp\left(-\gamma_b/2\right), \gamma_b = E_b/N_0$$
and the respective symbol error rate is (hard-decisions)
$$P_{es} = \frac{1}{2}\exp\left(-\gamma_b R_c/2\right), R_c = k/n < 1$$
- 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)

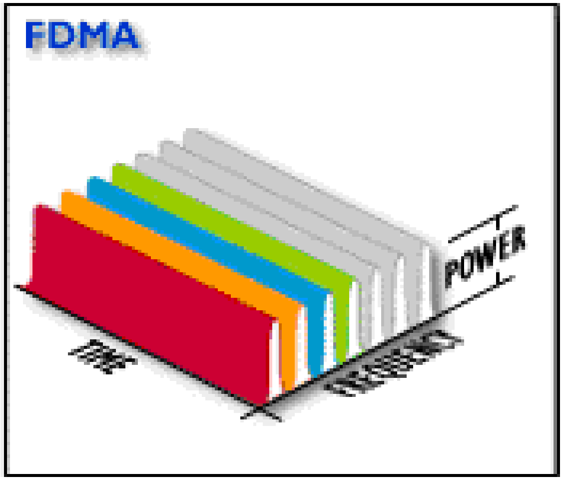
$$P_e = \frac{1}{2^{2L-1}}\exp\left(-\gamma_b/2\right)\sum_{i=0}^{L-1} K_i\left(\gamma_b/2\right)^i, \gamma_b = L\gamma_c$$

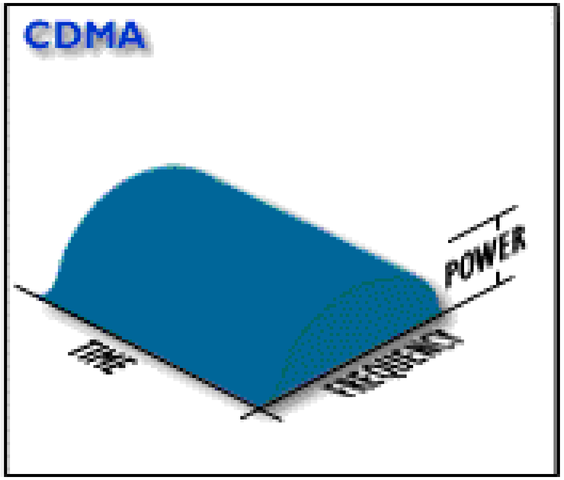
$$K_i = \frac{1}{i!}\sum_{r=0}^{L-1-i}\binom{2L-1}{r}$$

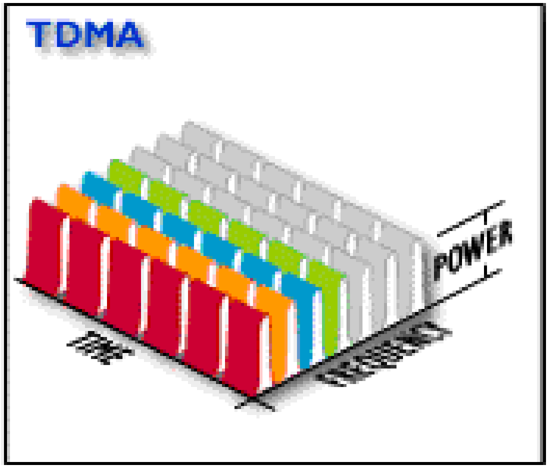
DS and FH compared

- 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,* $L_c \rightarrow 10^2 \ldots 10^7$
  - 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 on *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



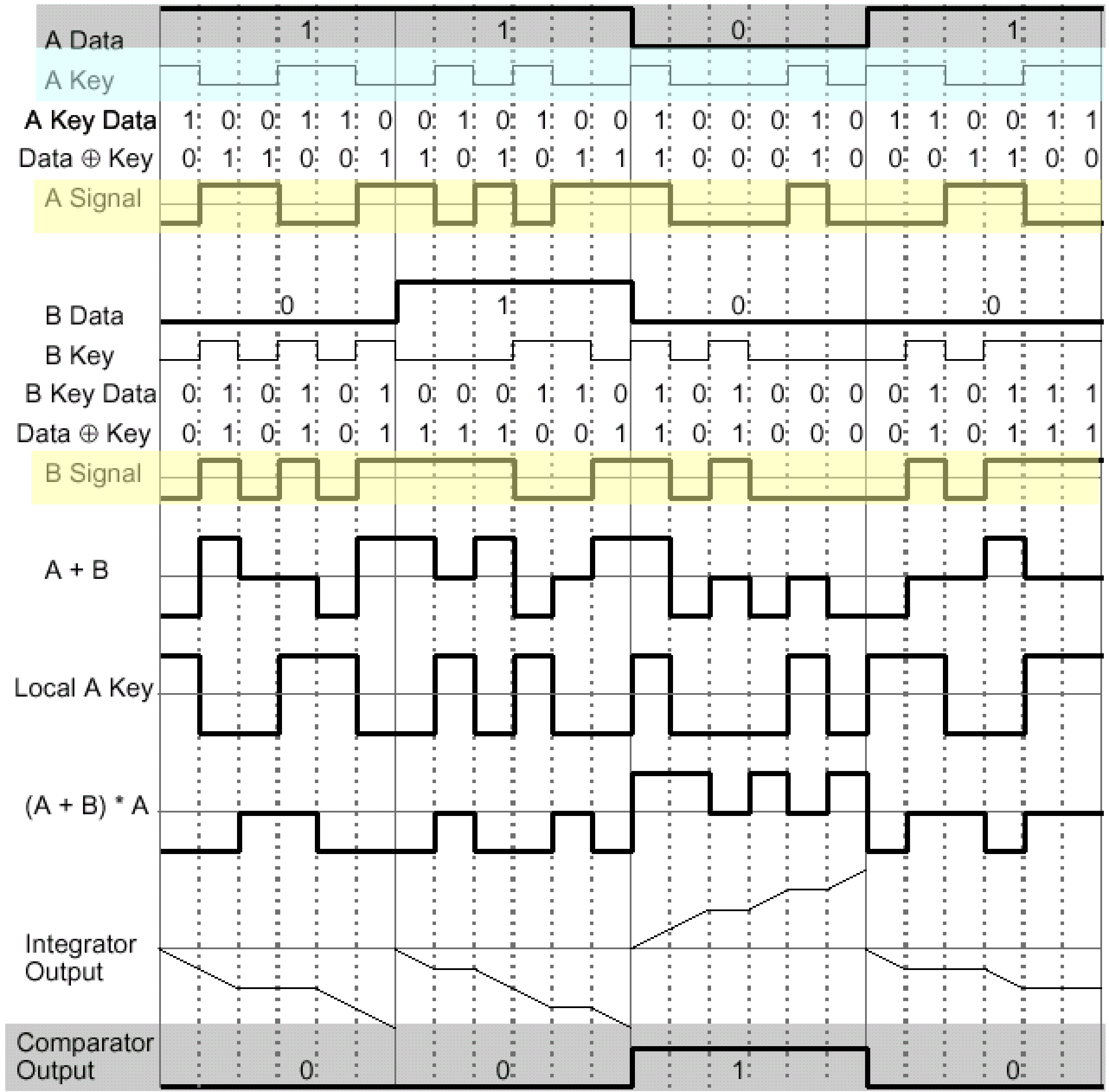




wireless communications

adaptive antennas, multiuser detection, FEC, and multi-rate encoding

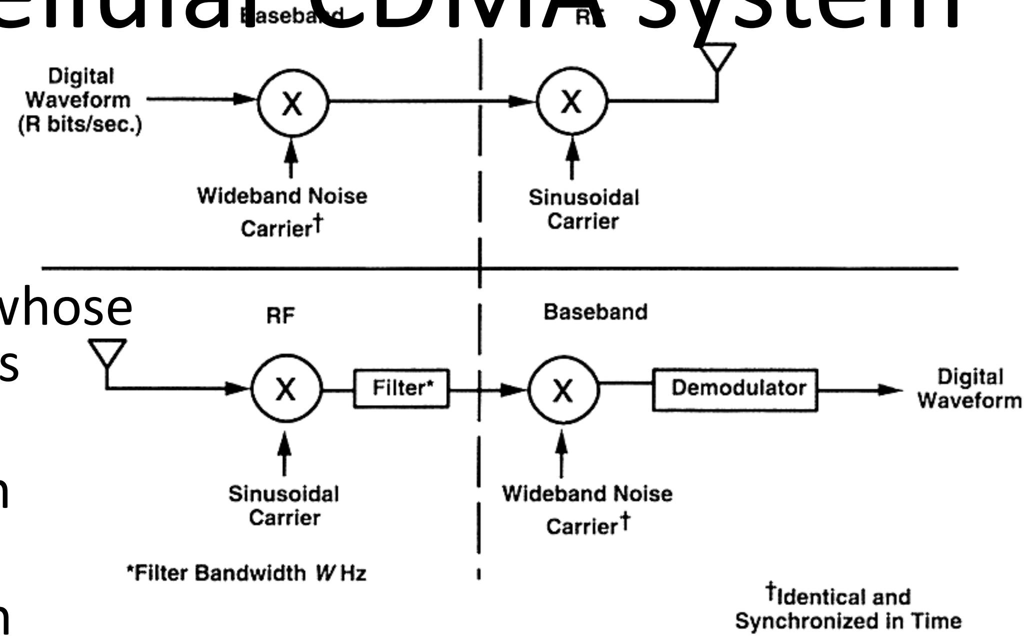
Example of DS multiple access



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

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

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

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)
  where B_T is the spreading (and RX) bandwidth
- Received signal energy / bit at the signaling rate R is

$$E_b = P_r / R \qquad [J] = [W][s]$$

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

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

- 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

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