Wireless Communications at the Physical Layer

Part 2: Techniques

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Outline

- Error compensation mechanisms
- Multiplexing at the physical layer
- Modulation
- Spread spectrum

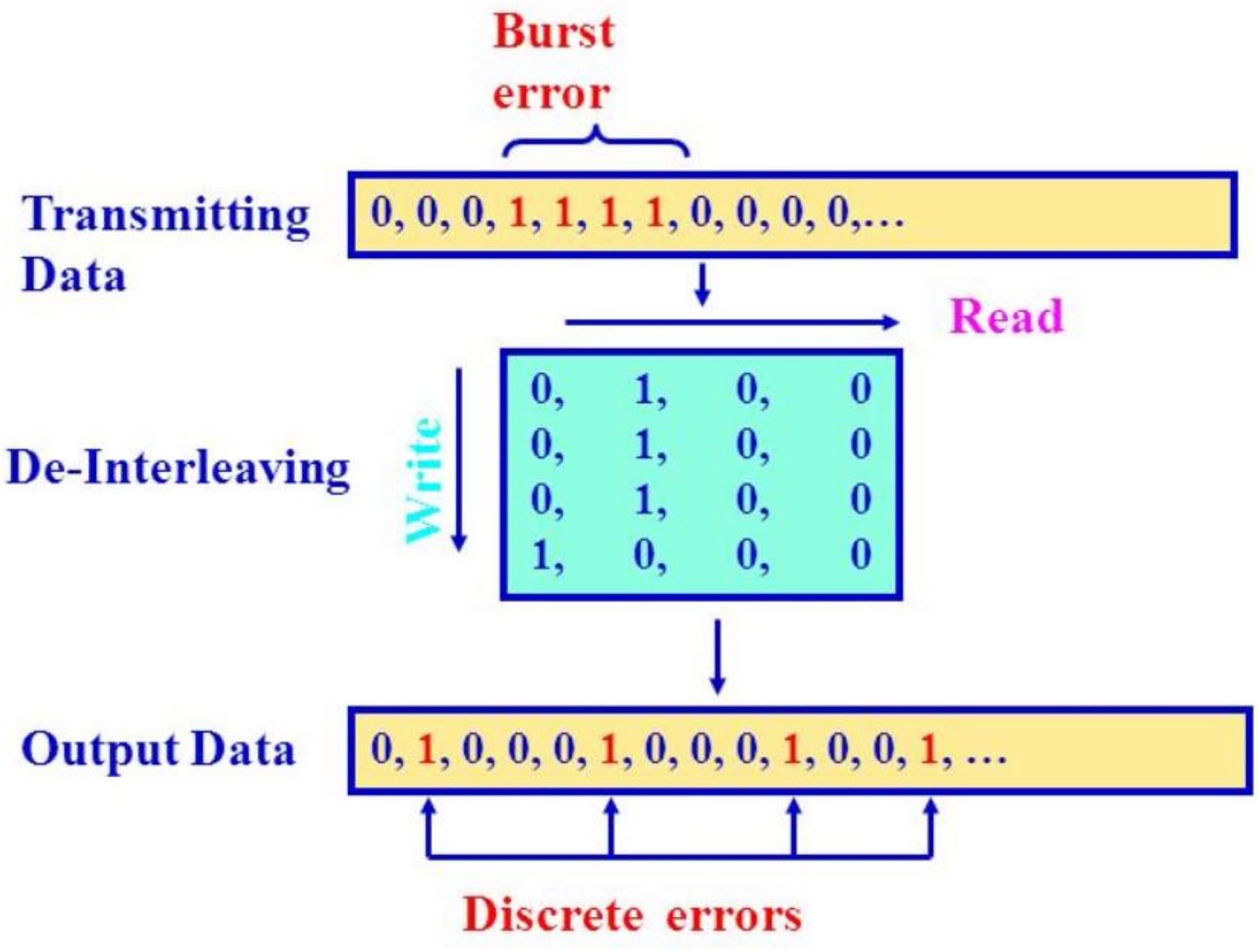
- Forward error correction
- Adaptive equalization
- Diversity techniques

Error compensation mechanisms

Forward Error Correction (FEC)

- Transmitter adds error-correcting code to data block
  - Code is a function of the data bits
- Receiver calculates error-correcting code from incoming data bits
  - If calculated code matches incoming code, no error occurred
  - If error-correcting codes don't match, receiver attempts to determine bits in error and correct them
- *k* data bits, *n* - *k* code bits => frame of *n* bits
  - FEC k/n
  - Example: FEC 1/3, FEC 2/3

Interleaving



Adaptive equalization

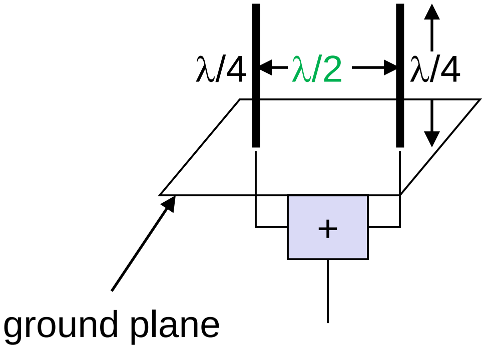
- Can be applied to transmissions that carry analog or digital information
- Used to combat intersymbol interference
- Involves gathering dispersed symbol energy back into its original time interval
- Typically, the transmitter sends a known sequence of bits (training sequence) periodically. The receiver compares the received TS with the expected TS in order to calculate the equalizations coefficients.

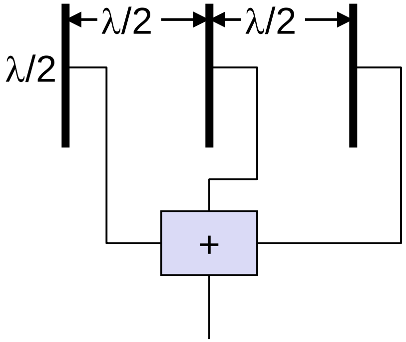
Diversity techniques

- Diversity is based on the fact that individual channels experience independent fading events
- Space/Antenna diversity – techniques involving different physical transmission paths
- Frequency diversity – techniques where the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers
- Time diversity – techniques aimed at spreading the data out over time (e.g. repetition, interleaving)

Antenna diversity

- Grouping of 2 or more antennas
  - multi-element antenna arrays
- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain





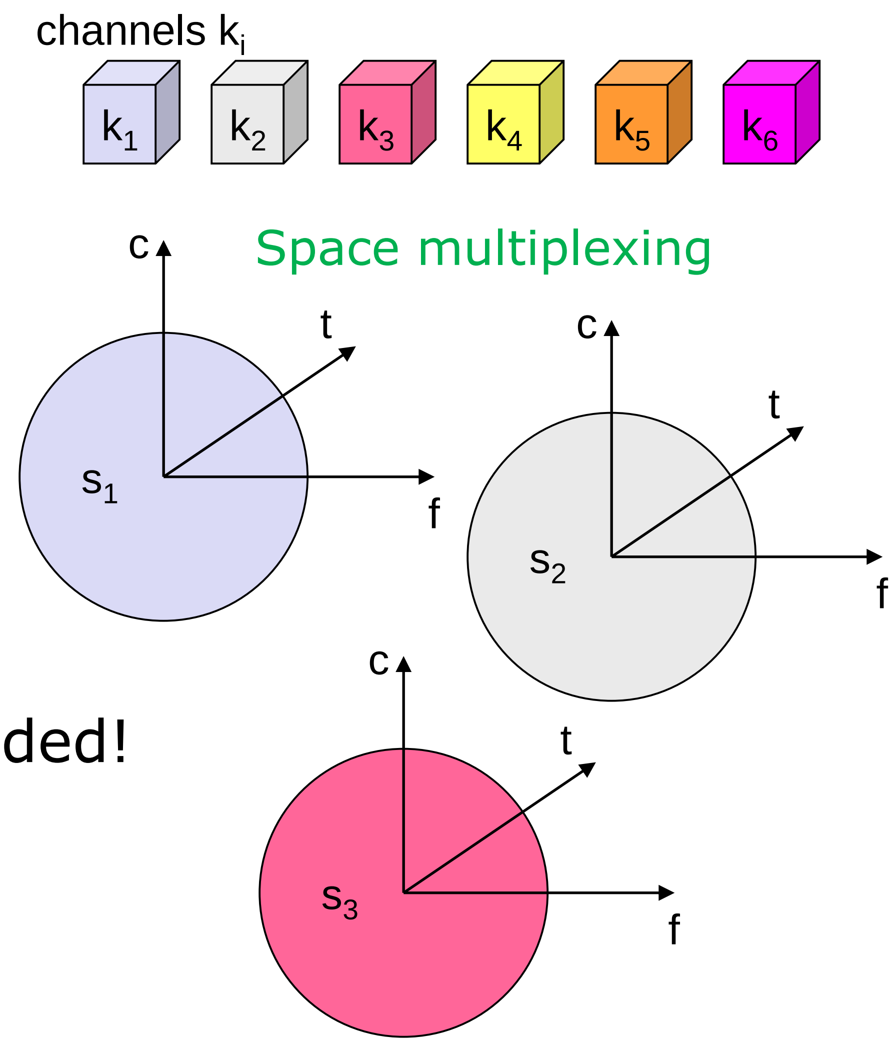
Multiplexing at the physical layer

Multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

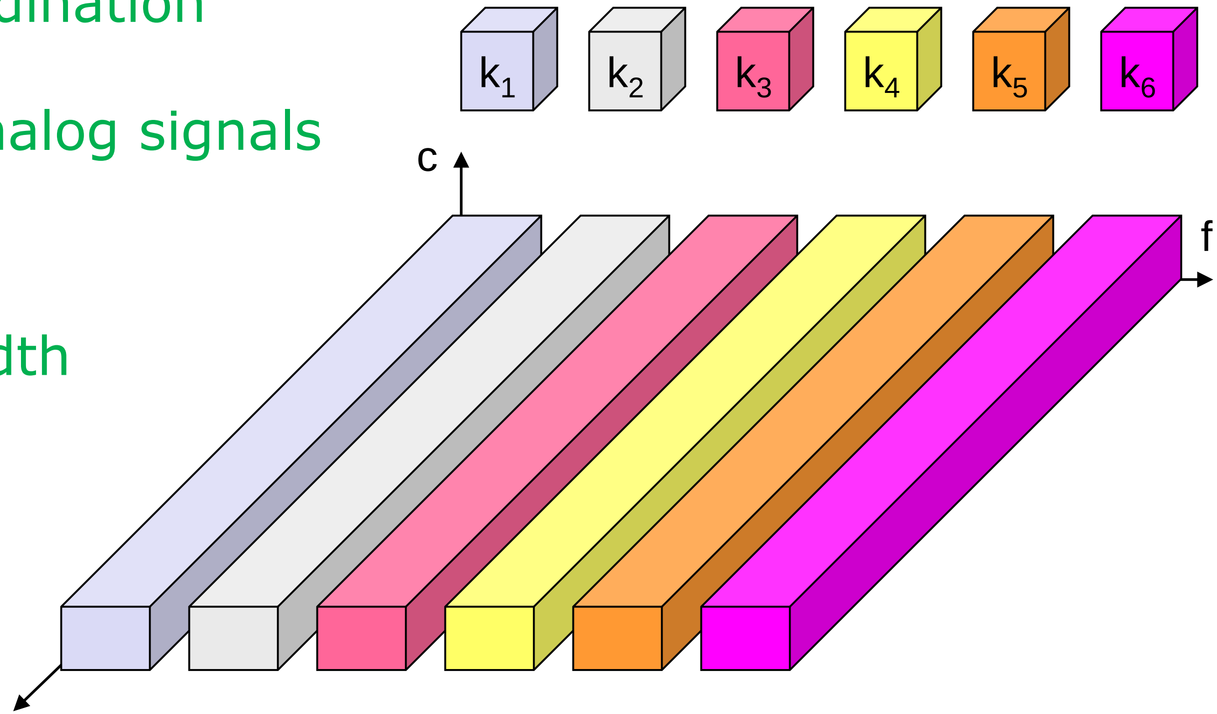
- Goal: multiple use of a shared medium

- Important: guard spaces needed!



Frequency multiplexing (FDM)

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible

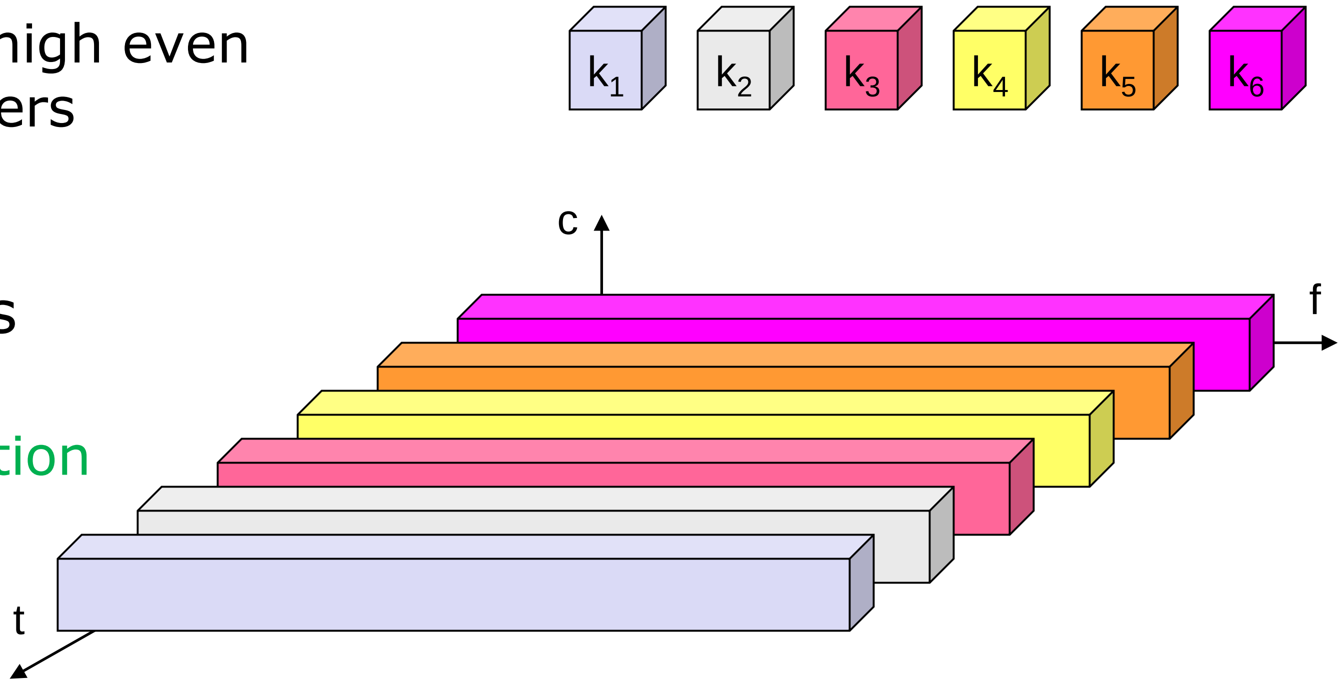


Time multiplexing (TDM)

- A channel gets the whole spectrum for a certain amount of time

- Advantages
  - only one carrier in the medium at any time
  - throughput high even for many users
  - flexible

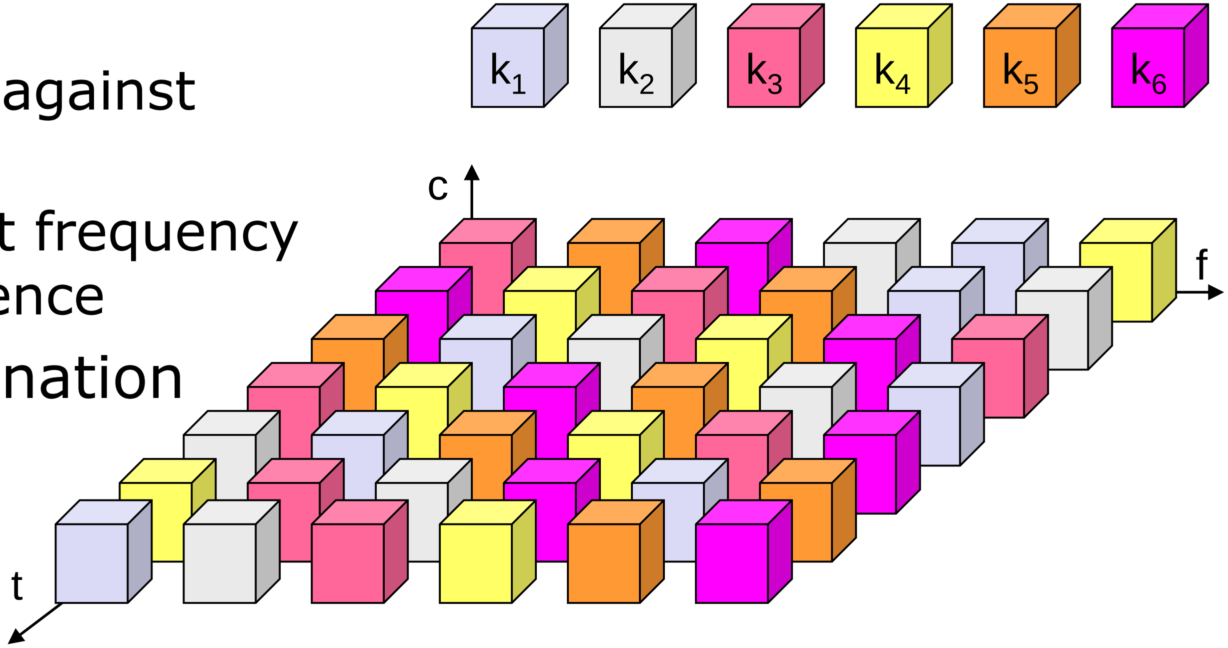
- Disadvantages
  - precise synchronization necessary



Time and frequency multiplexing

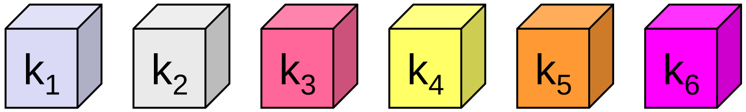
- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM

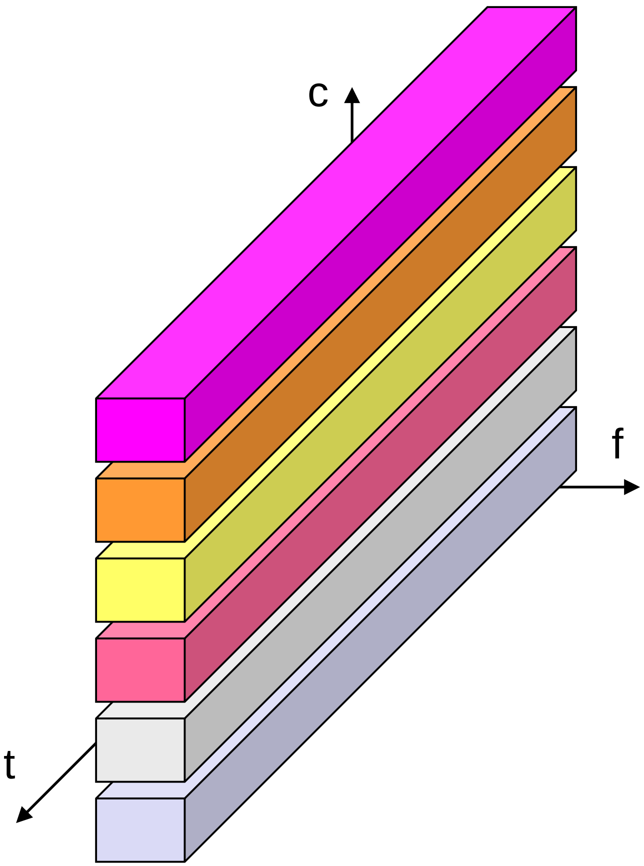
- Advantages
  - better protection against tapping
  - protection against frequency selective interference
- but: precise coordination required



Code multiplexing (CDM)

- Each channel has a unique code





- All channels use the same spectrum at the same time
- Advantages
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages
  - varying user data rates
  - more complex signal regeneration
- Implemented using spread spectrum technology

- Introduction
- Analog modulation techniques
- Digital modulation techniques

Modulation

Modulation

- Basics: Transmitter sends a modulated radio wave, receiver can detect whether such a wave is present and also its parameters
- Parameters of a wave = sine function (**carrier**):

$$s(t) = A(t)\,\mathrm{sin}(2\pi f(t)t + \phi(t))$$

  - Parameters: amplitude A(t), frequency f(t), phase ϕ(t)

- Manipulating these three parameters allows the sender to express data; receiver reconstructs data from signal

Receiver: Demodulation

- The receiver looks at the received wave form and matches it with the signal that caused the transmitter to generate this wave form
  - Necessary: one-to-one mapping between data and wave form
- Problems caused by
  - Carrier synchronization: frequency can vary between sender and receiver (drift, temperature changes, aging, …)
  - Bit synchronization (actually: symbol synchronization): When does symbol representing a certain bit start/end?
  - Frame synchronization (is a concern of data link layer): When does a packet start/end?
  - Biggest problem: Received signal is ***not*** the transmitted signal (can suffer deterioration during transmission).

Motivations for modulation

- An antenna must have a size the same order of magnitude of the signal’s wavelength to be effective
- Modulation enables frequency division multiplexing
- The propagation characteristics of a medium (e.g. attenuation) vary with the frequency of the signal. Modulation allows the choice of an adequate carrier frequency

Analog Modulation Techniques

- Analog data to analog signal
  - Amplitude modulation (AM)
  - Angle modulation
    - Frequency modulation (FM)
    - Phase modulation (PM)

- Amplitude Modulation

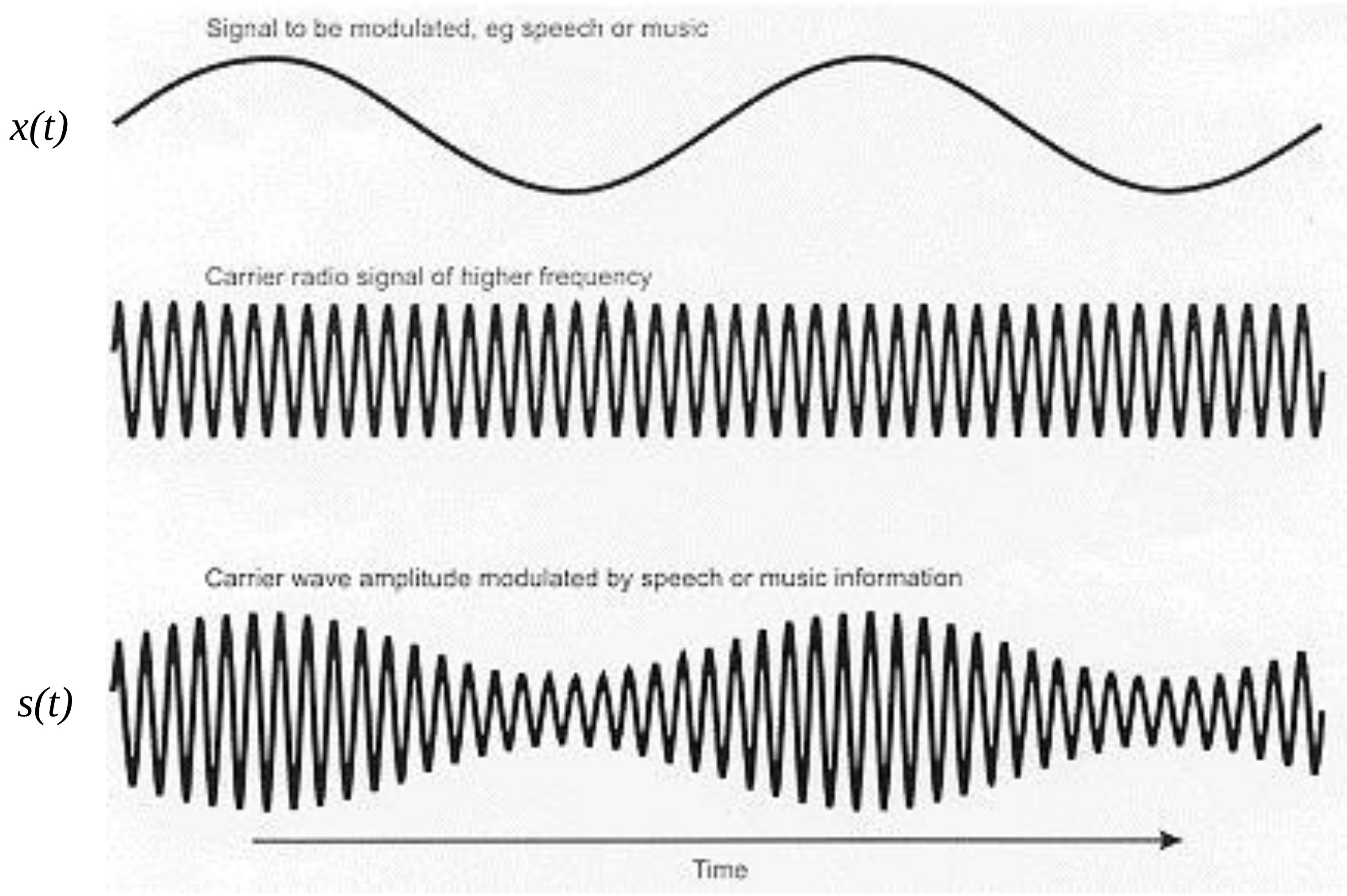
$$s(t) = [1 + n_a x(t)]\cos 2\pi f_c t$$

  - $c(t)$ = $\cos 2\pi f_c t$ = carrier
  - $x(t)$ = input signal
    - modulating signal -> $x(t) = m(t)$
  - n_a = modulation index
    - Ratio of amplitude of input signal to carrier

  - AM modulation principle
    - Uses quadratic (non-linear) function
    - Filters only desired frequency components

$$(m + c)^2 = m^2 + \boldsymbol{2mc} + c^2$$

Waveform of an AM signal



Amplitude Modulation

- Given a sinusoidal modulating signal

$$x(t) = \cos 2\pi f_m t$$

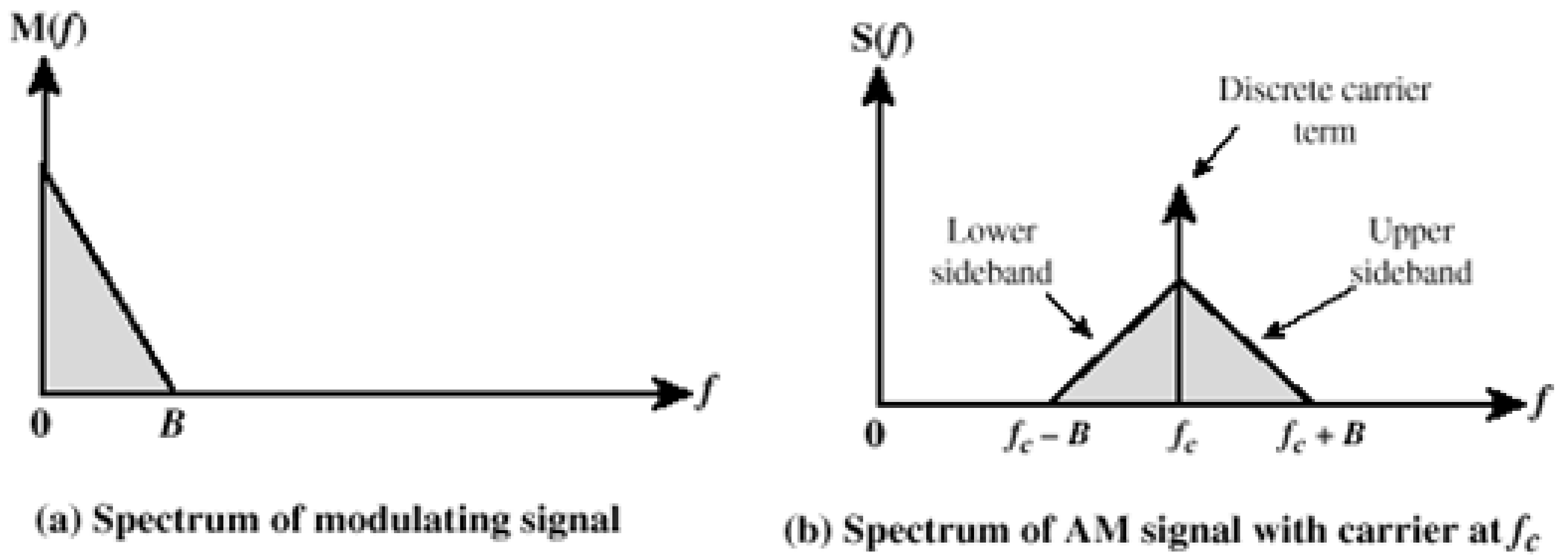
- By using the trigonometric identity

$$\cos(a)\cos(b) = \frac{1}{2}\left(\cos(a+b) + \cos(a-b)\right)$$

- The modulated signal can be expressed as

$$s(t) = \cos 2\pi f_c t + \frac{n_a}{2}\cos 2\pi(f_c - f_m)t + \frac{n_a}{2}\cos 2\pi(f_c + f_m)t$$

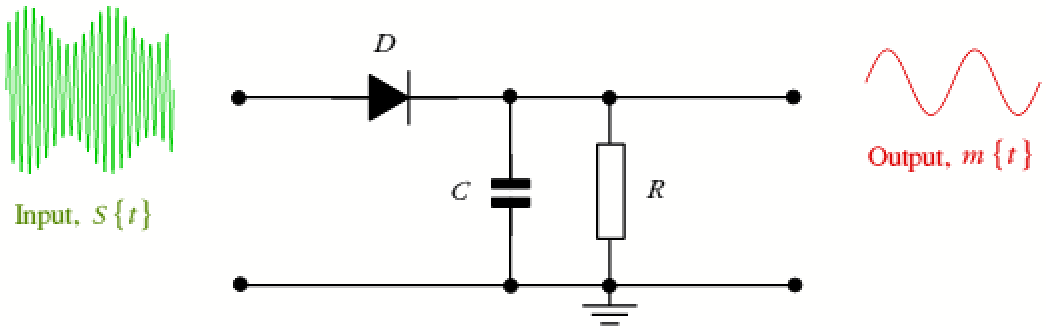
Spectrum of an AM signal

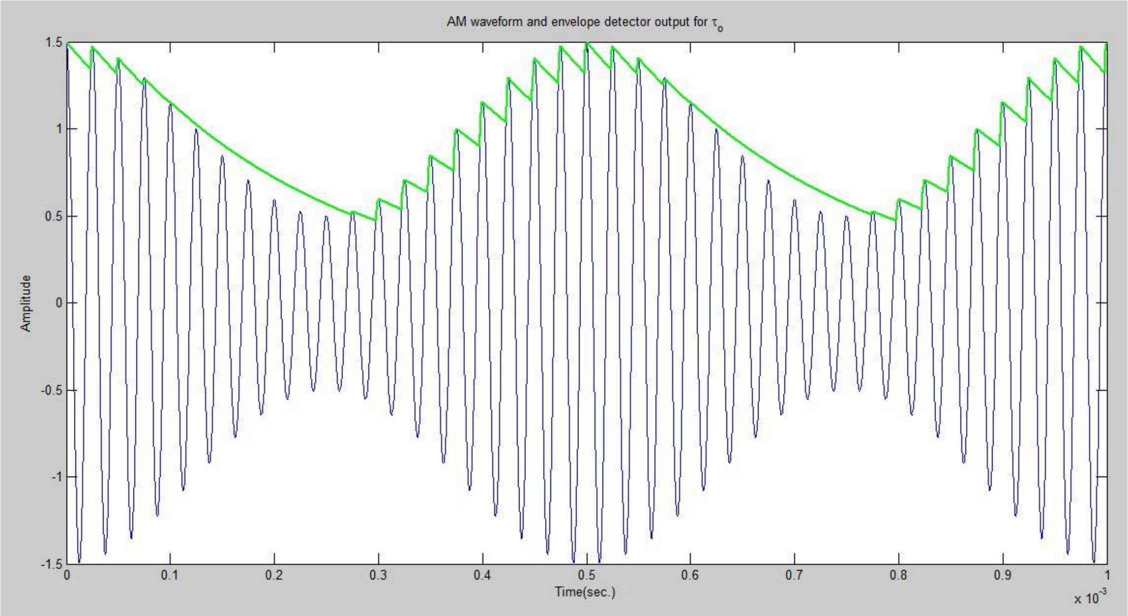


- Above example is know as AM-DSB – Double Sideband

Envelope detector

- Basic type of AM demodulator





Other AM variants

- Single Sideband (SSB)
  - Sends only one sideband
  - Eliminates other sideband and carrier
  - Advantages
    - Only half the bandwidth is required
    - Less power is required
  - Disadvantages
    - Suppressed carrier can’t be used for synchronization purposes
- Double sideband suppressed carrier (DSB-SC): filters out the carrier frequency and sends both sidebands.
- Vestigial sideband (VSB): uses one sideband and reduced-power carrier and a vestige of the other sideband (used by TV broadcasting)

Angle Modulation

$$s(t) = A_c \cos[2\pi f_c t + \phi(t)]$$

- Phase modulation
  - Phase is proportional to modulating signal

$$\phi(t) = n_p m(t)$$

    - n_p = phase modulation index
- Frequency modulation
  - Derivative of the phase is proportional to modulating signal

$$\phi'(t) = n_f m(t)$$

    - n_f = frequency modulation index

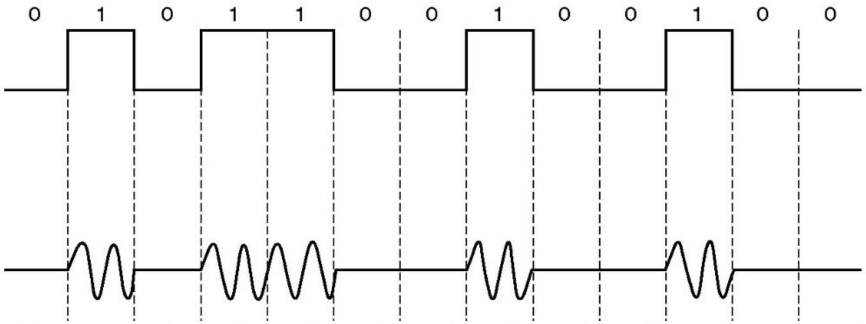
Angle Modulation

- Compared to AM, FM and PM result in a signal whose bandwidth:
  - is also centered at f_c
  - but has a pattern that is much different
    - Angle modulation includes $\cos(\varnothing(t))$ which produces a wide range of frequencies

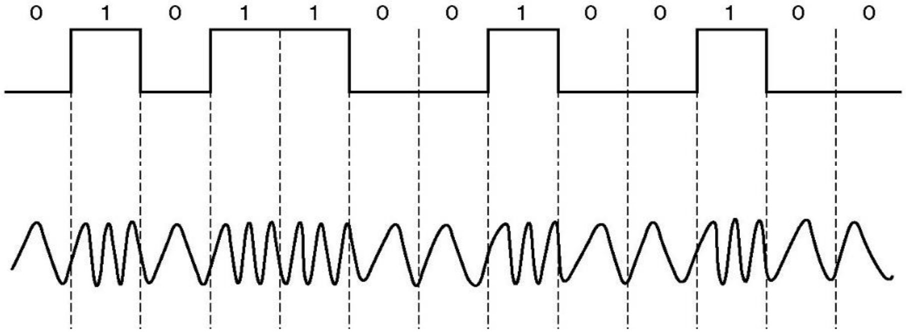
Digital modulation techniques

- Modulation using digital signals is known as Shift Keying

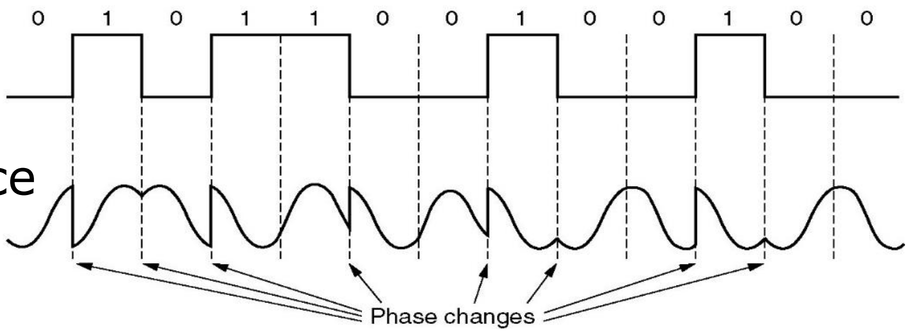
- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference



- Frequency Shift Keying (FSK):
  - needs larger bandwidth

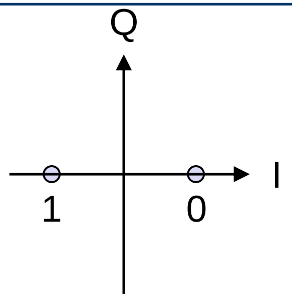


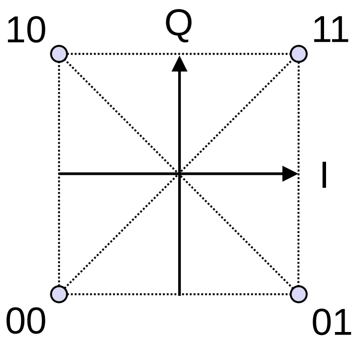
- Phase Shift Keying (PSK):
  - more complex
  - more robust against interference

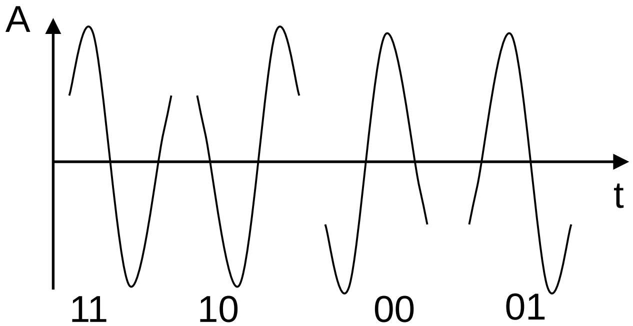


Advanced Phase Shift Keying

- BPSK (Binary Phase Shift Keying):
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used e.g. in satellite systems
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex
- Often also transmission of relative, not absolute phase shift: DPSK - Differential PSK

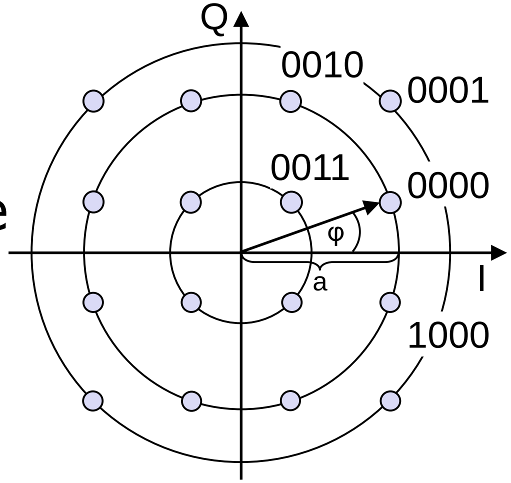






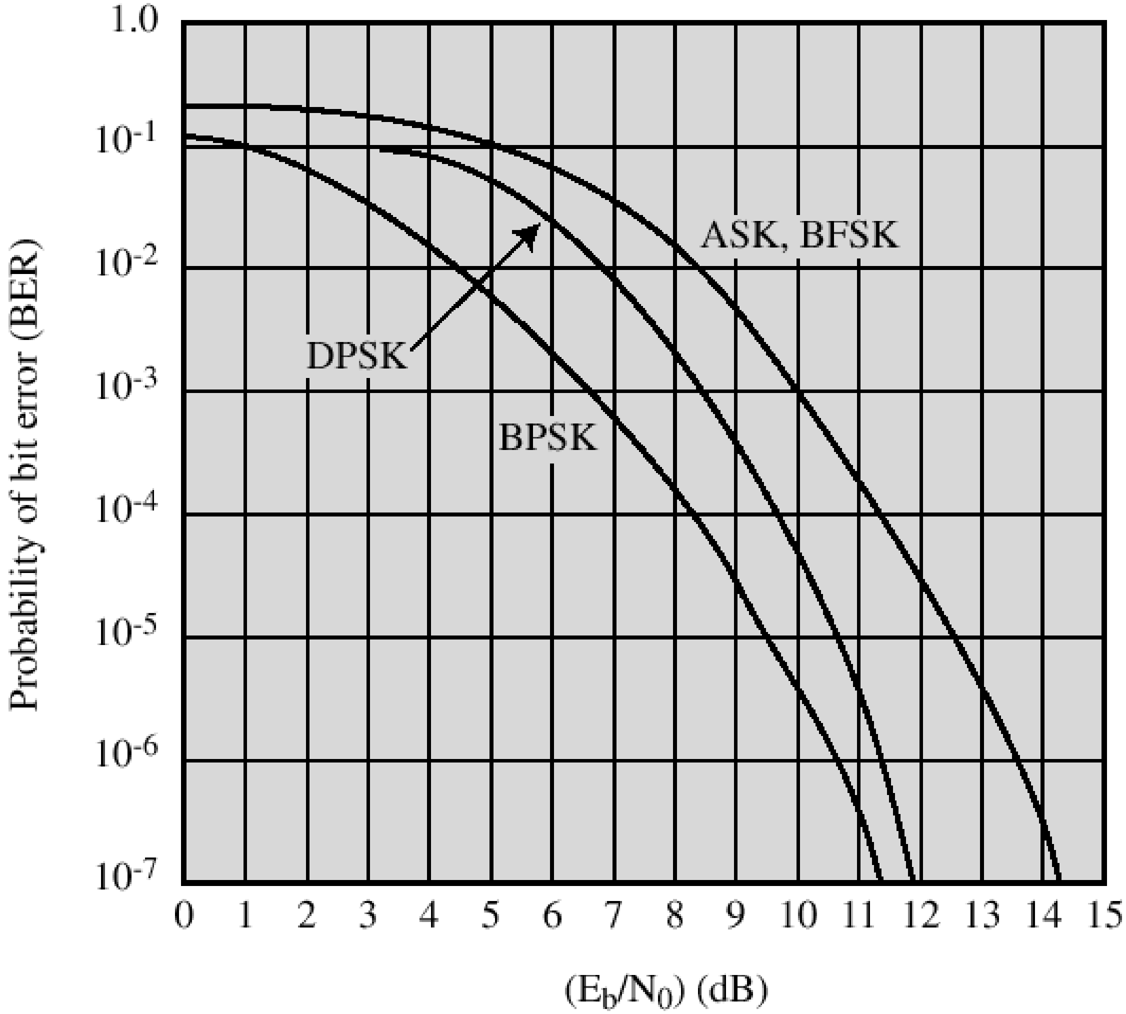
Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM)
  - combines amplitude and phase modulation
  - it is possible to code n bits using one symbol
  - $M=2^n$ discrete levels, n=2 identical to QPSK
- Bit error rate increases with n, but less errors compared to comparable PSK schemes
  - Example: 16-QAM (4 bits = 1 symbol)
  - Symbols 0011 and 0001 have the same phase φ, but different amplitude ; symbols 0000 and 1000 have different phase, but same amplitude.

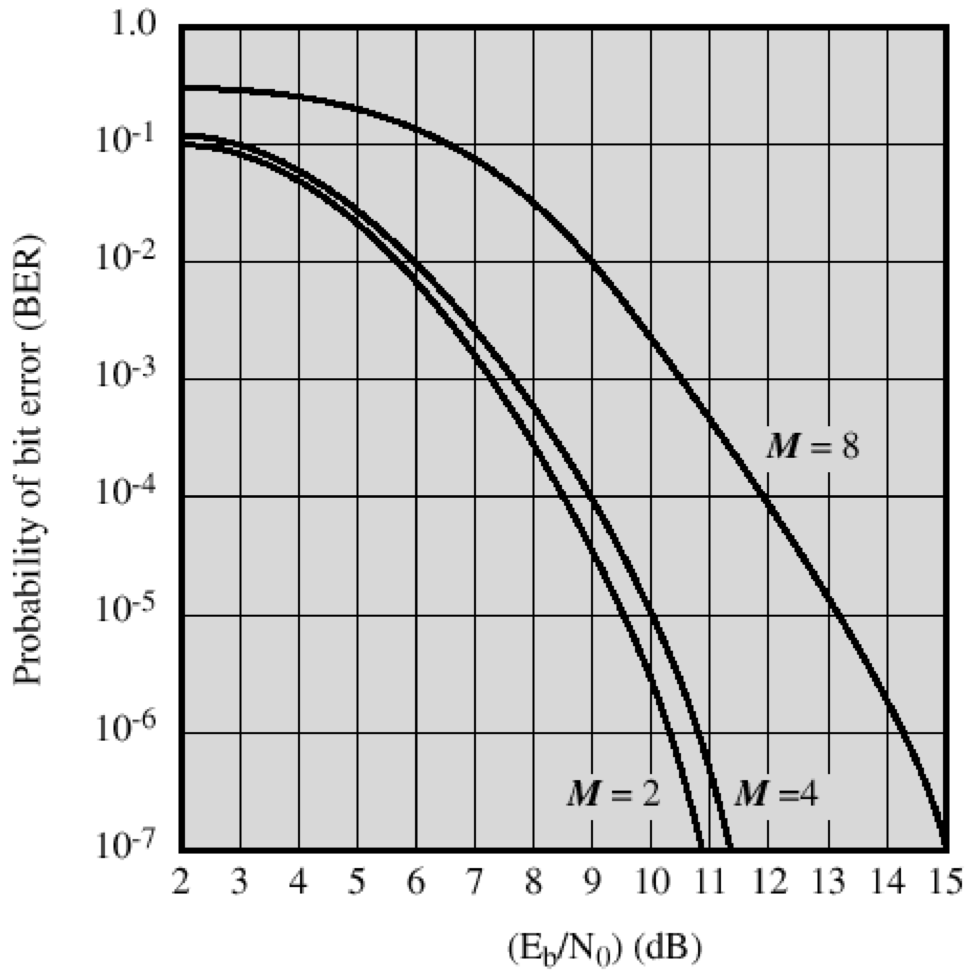


- Constellation diagram – Representation of modulation symbols on plane

Performance of binary modulations



Performance of multilevel PSK

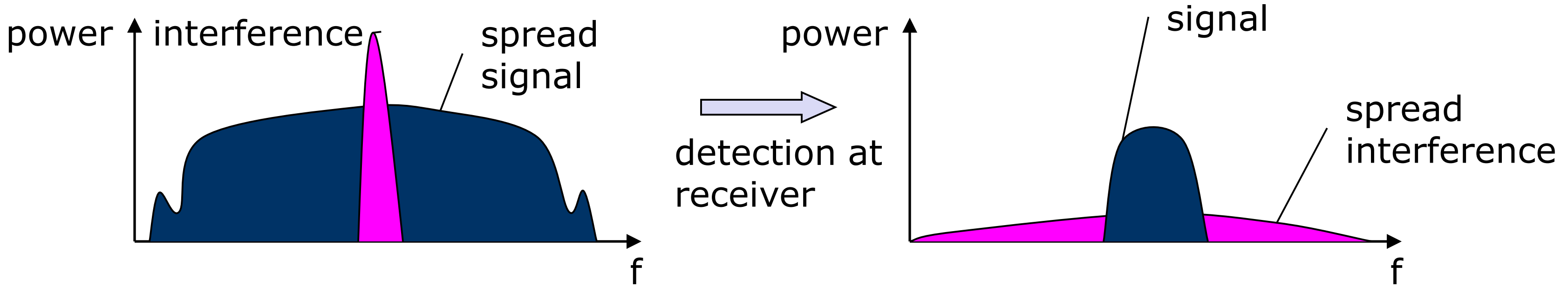


(b) Multilevel PSK (MPSK)

Spread spectrum

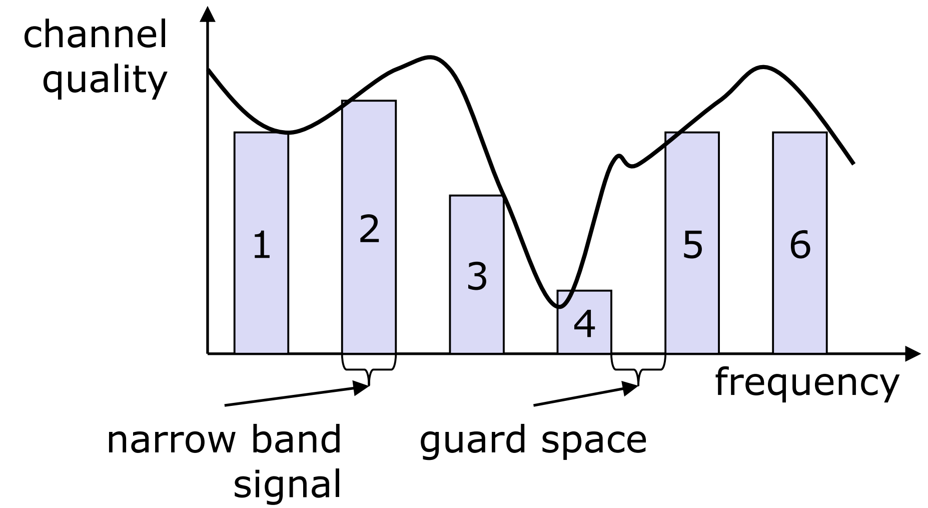
Spread spectrum technology

- Problem of radio transmission: frequency dependent fading and interference can wipe out narrow band signals
- Solution: spread the narrow band signal into a broad band signal using a special code
  - protection against narrow band interference

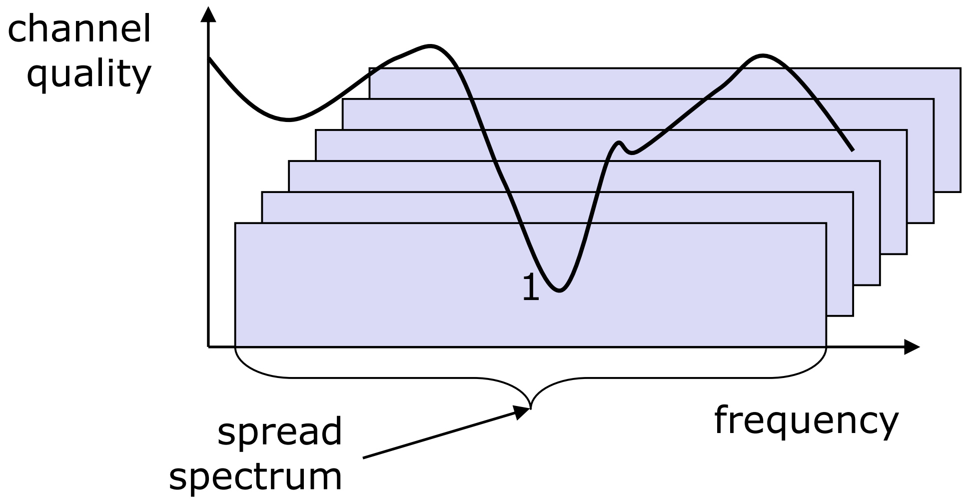


- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Modalities: Direct Sequence, Frequency Hopping

Spreading and frequency selective fading



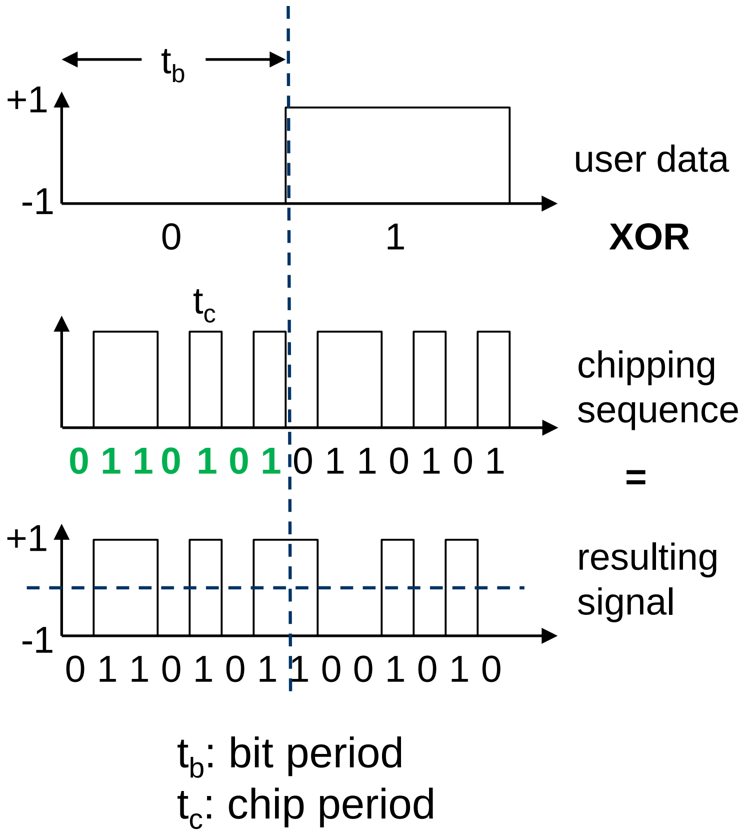
narrowband channels



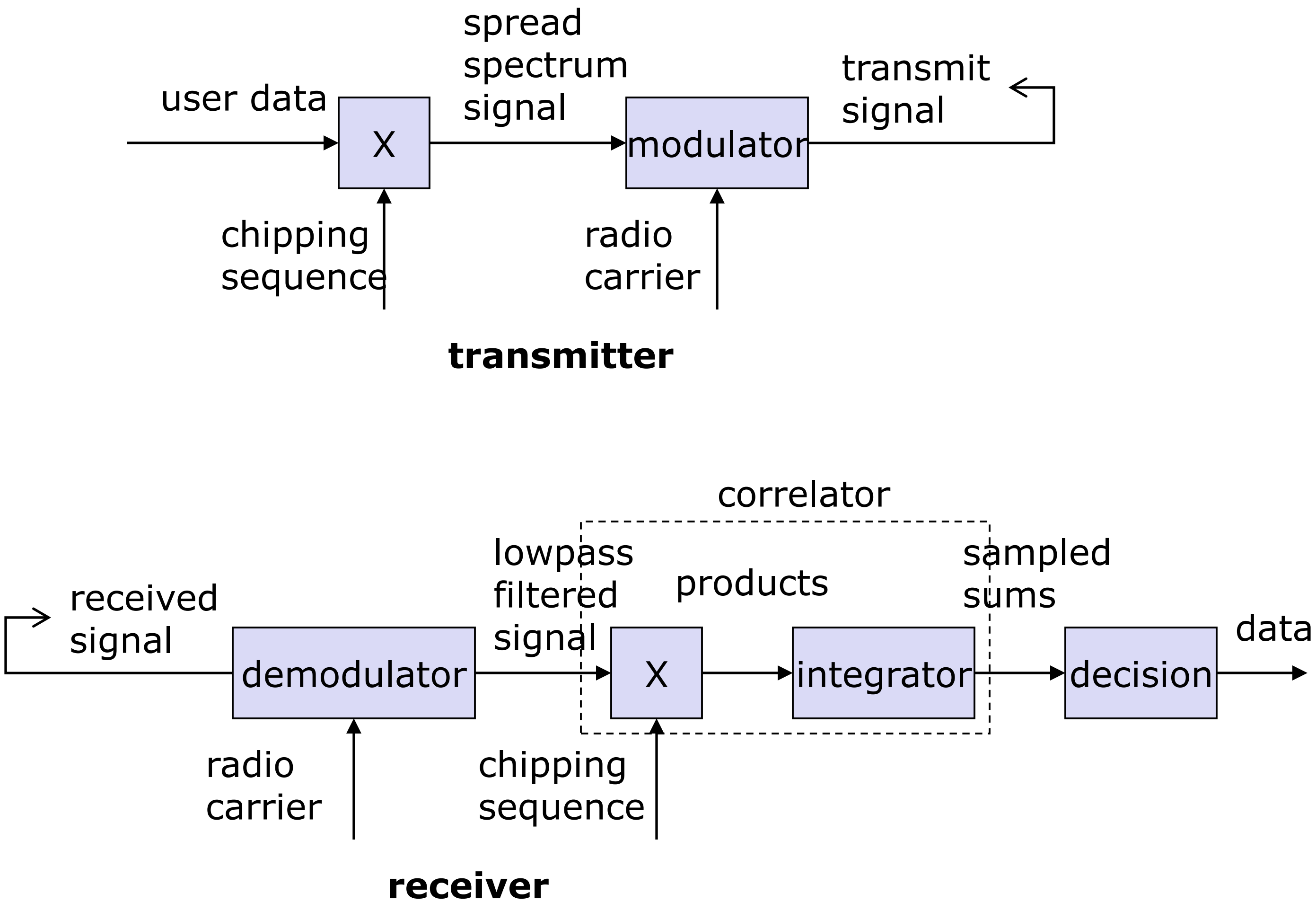
spread spectrum channels

DSSS (Direct Sequence Spread Spectrum)

- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover
- Disadvantages
  - precise power control necessary



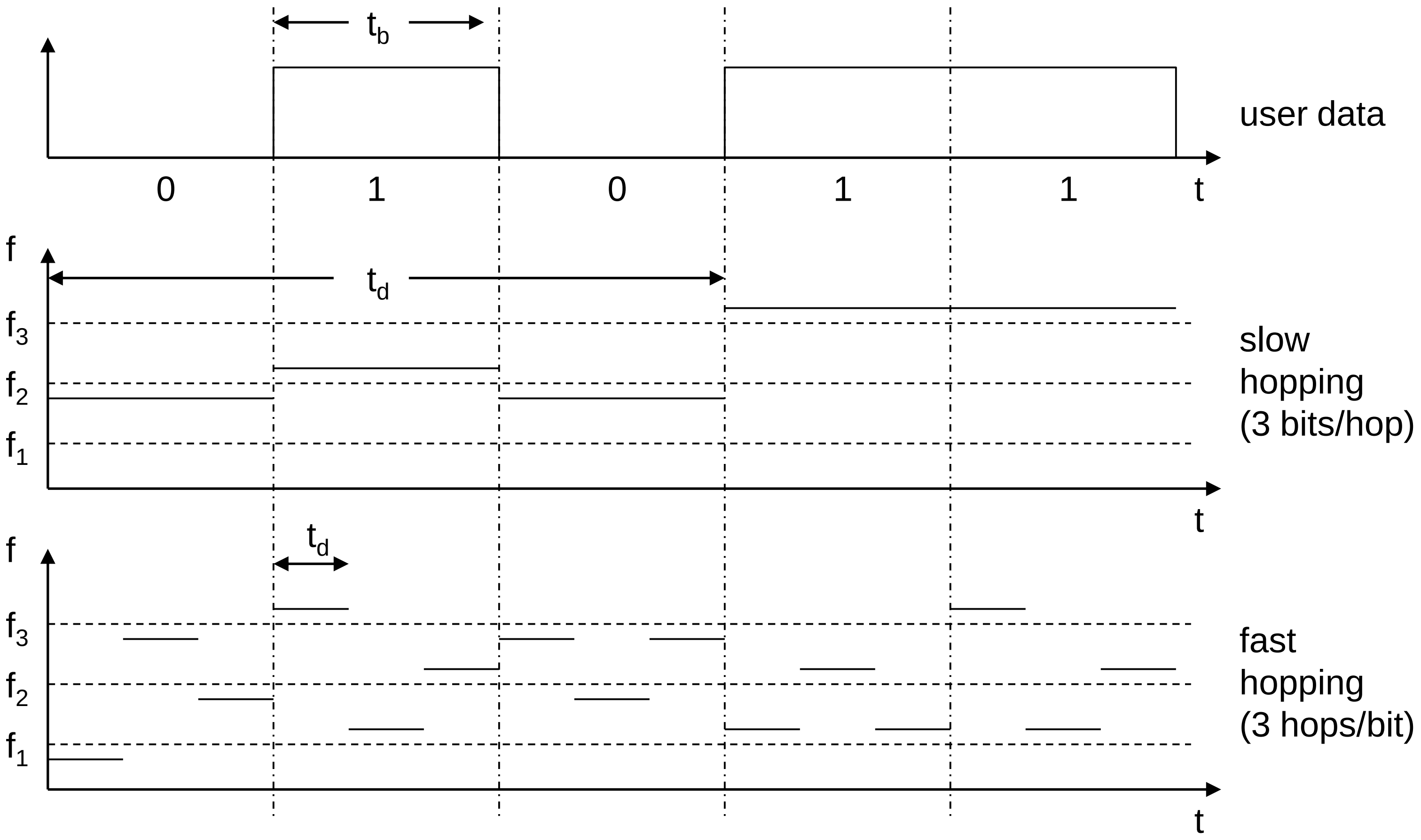
DSSS (Direct Sequence Spread Spectrum)



FHSS (Frequency Hopping Spread Spectrum)

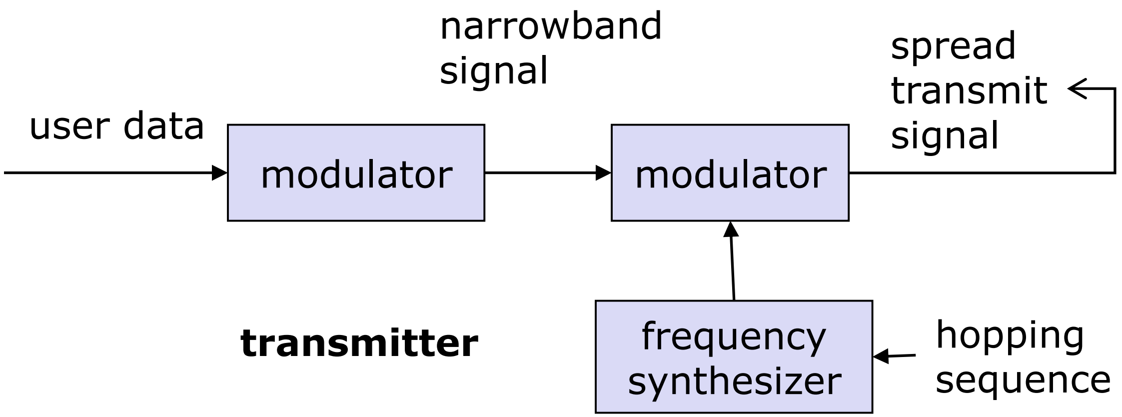
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect

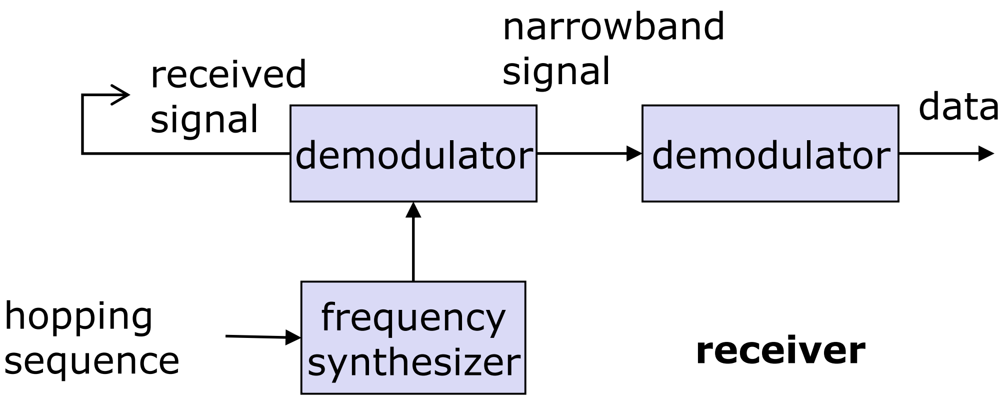
FHSS (Frequency Hopping Spread Spectrum)



t_b: bit period t_d: dwell time

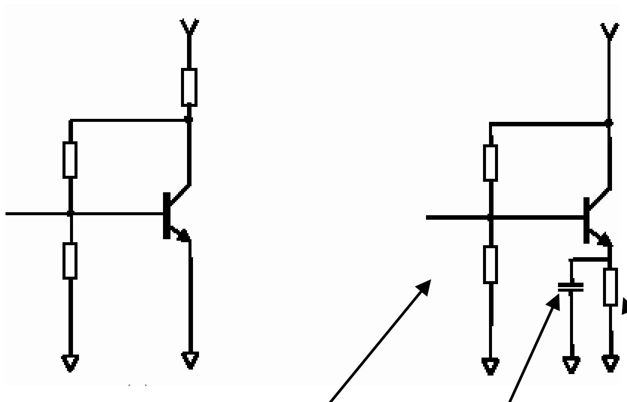
FHSS (Frequency Hopping Spread Spectrum)





Amplificador

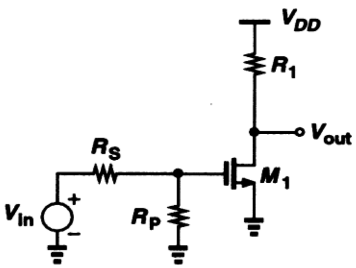
Soluções para baixa frequência

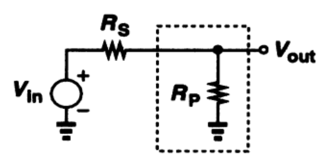


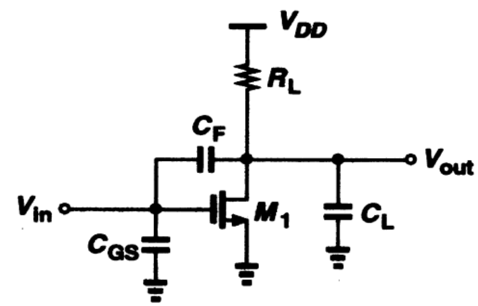
Sensível a variações
da tensão de alimentação

Condensador de bypass pode causar alguma instabilidade em RF e a resistência pode introduzir ruído

Soluções para alta frequência







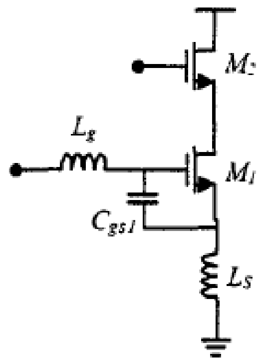
Factor de ruído elevado

$$F \geq 2 + \frac{4\gamma}{\alpha} \cdot \frac{1}{g_m R},$$

$$R_S = R_1 = R.$$

Problema de estabilidade

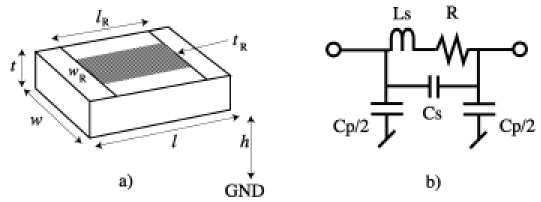
Soluções para alta frequência



Amplificador em cascata com degeneração indutiva da fonte

$$Z_{in} = s(L_g + L_s) + \frac{1}{sC_{gs1}} + R_g + R_1 + \frac{g_{m1}}{C_{gs1}} L_s$$

Dispositivos passivos



Resistência SMD

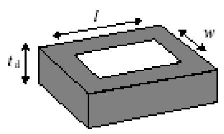
$$R = l_R / (\sigma_R\, w_R\, t_R) = R_p\, l_R / w_R$$

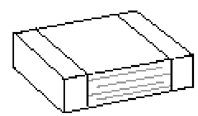
$$L_S = 0.125\, l_R \left(\ln\left[2\, l_R / w_R\right] + 0.5 + 2\, w_R / 9\, l_R \right) \mu H$$

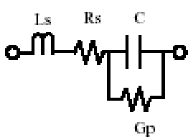
$$C_P = \varepsilon\, w_E\, l_R / h$$

Dispositivos passivos

Condensador SMA







Pratos paralelos

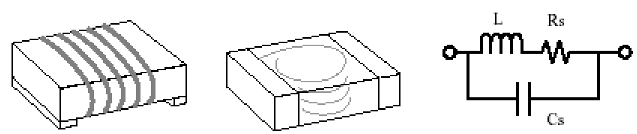
Multi-nível

$$C = \varepsilon w l / t_d$$

$$C_p = (n-1)\varepsilon w_p l / t_L$$

Dispositivos passivos

Indutância SMA



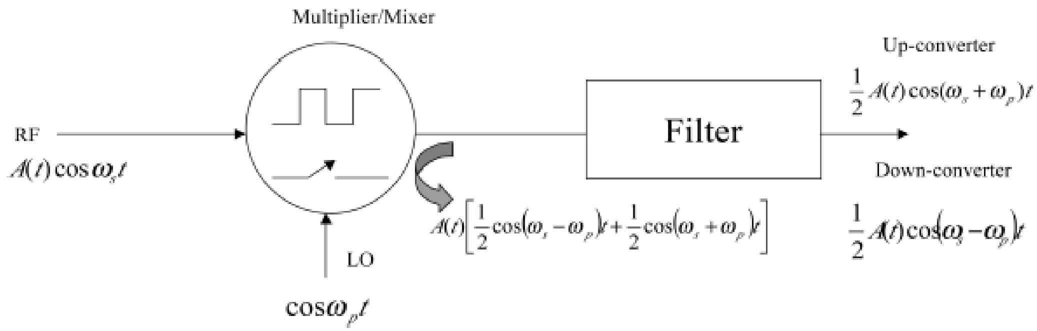
$$L = 9.825\, n^2 d^2 / (4.5\, d + 10\, l)\ \mu H$$

Mixer

Tipos de Mixer

- Up-Converter $w_{IF}=(w_r+w_{LO})$
- Down-Converter $w_{IF}=|w_r-w_{LO}|$
- Harmonic $w_{IF}=nw_{LO}- w_r$

Mixer ideal



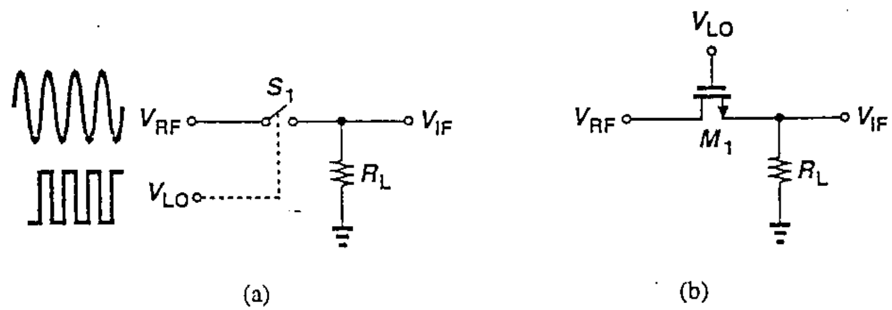
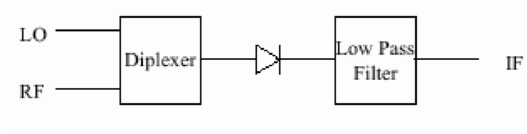
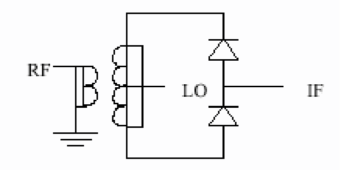


Figure 6.15 (a) Simple switch used as mixer, (b) implementation of switch with an NMOS device.

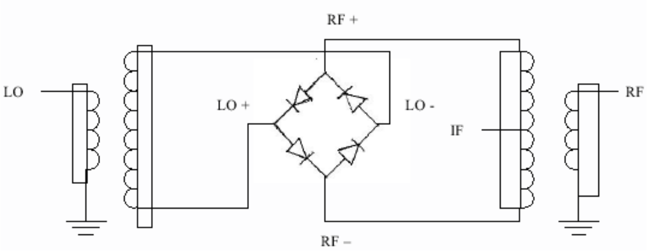
Solução com díodos $I(V) = I_s(e^{\alpha V} - 1),$



Single ended



Single balanced



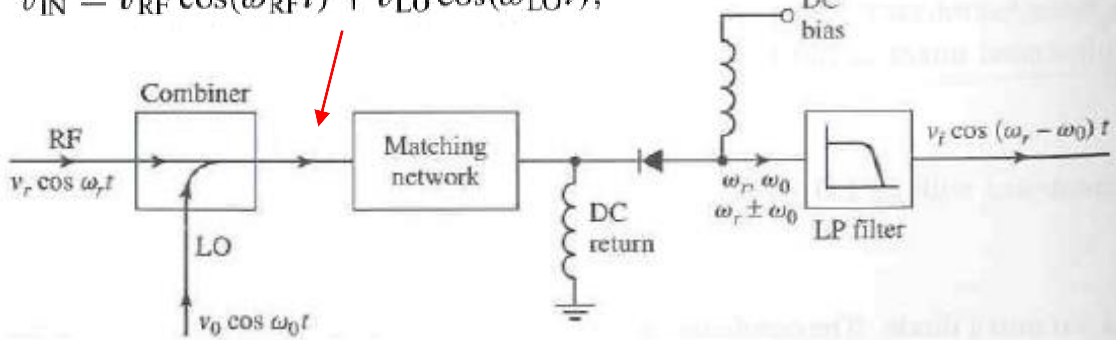
Double balanced

Microwave, Pozar

Mixer com Díodos

- Single-ended

$$v_{IN} = v_{RF}\cos(\omega_{RF}t) + v_{LO}\cos(\omega_{LO}t),$$



$$i = \frac{G_d'}{2}(v_r \cos \omega_r t + v_0 \cos \omega_0 t)^2 \qquad I(V) = I_0 + v\left.\frac{dI}{dV}\right|_{V_0} + \frac{1}{2}v^2\left.\frac{d^2I}{dV^2}\right|_{V_0} + \cdots,$$

$$= \frac{G_d'}{4}[v_r^2 + v_0^2 + v_r^2 \cos 2\omega_r t + v_0^2 \cos 2\omega_0 t$$
$$+ 2v_r v_0 \cos(\omega_r - \omega_0)t + 2v_r v_0 \cos(\omega_r + \omega_0)t].$$

Misturador - Multiplicador

$$V_{RF}(t) = A_{RF}\cos\omega_{RF}t$$

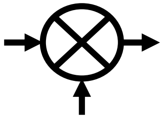
$$V_{LO}(t) = A_{LO}\cos\omega_{LO}t$$

$$V_{RF}(t)\cdot V_{LO}(t) = \frac{A_{RF}A_{LO}}{A_{REF}}\left(\cos(\omega_{RF}-\omega_{LO})t + \cos(\omega_{RF}+\omega_{LO})t\right)$$

$$CG = \frac{A_{LO}}{A_{REF}} \Rightarrow$$

É necessária uma amplitude de LO elevada para aumentar o ganho

$$V_{RF}(t) = A_{RF}\cos\omega_{RF}t$$



$$V_{LO}(t) = A_{LO}\cos\omega_{LO}t$$

Parâmetros de um mixer

- Ganho de conversão – relação entre a saída IF desejada e o valor da entrada RF

- NF – Relação entre SNR no porto RF e SNR no porto IF – (SSB > DSB porque não existe sinal numa das bandas)

- Isolamento – LO-IF e LO-RF (perturba os andares a seguir ao de IF ou pode radiar)

Parâmetros

Conversão de frequência

- superior
- inferior

Rejeição de imagem

Factor de ruído (1-5 dB)

Perdas de conversão (4-7 dB)

Perdas resistivas

Perdas no processo de conversão

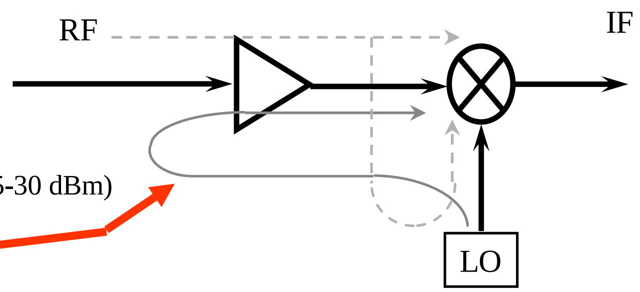
Distorção de intermodulação (P_3 = 15-30 dBm)

Isolamento (20-40 dB)

- entre RF e LO, energia do LO pode ser radiada pela antena

TABLE 6.2 Typical mixer characteristics.

NF	12 dB
IIP_3	+5 dBm
Gain	10 dB
Input Impedance (Heterodyne)	50 Ω
Port-to-Port Isolation	10–20 dB



Transceiver