Lecture 14
The grand tour

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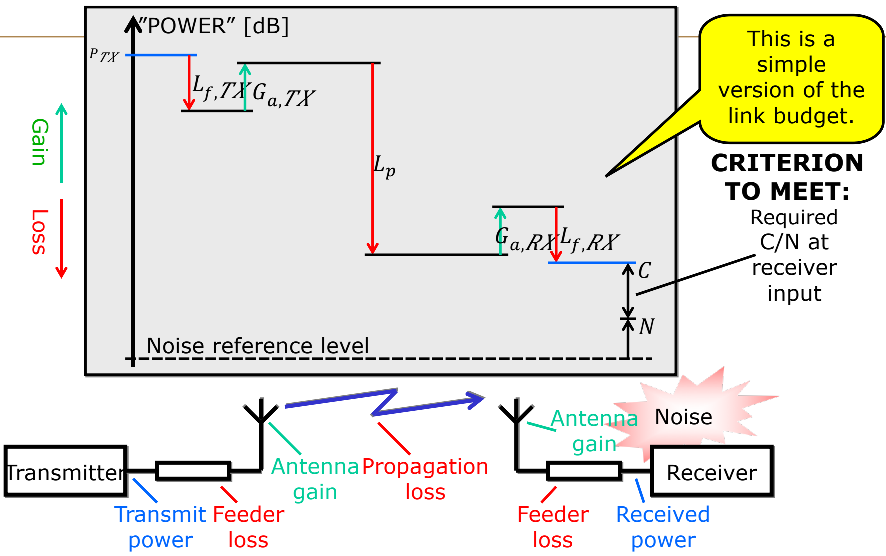
Link budget



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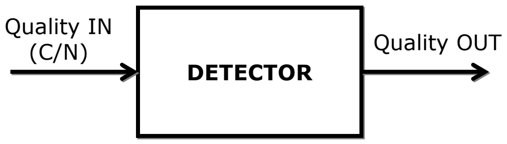
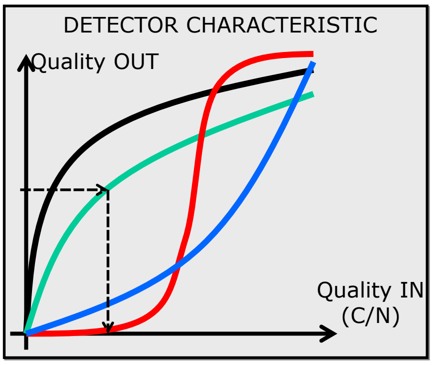
Required C/N





The detector characteristic is different for different system design choices.

REQUIRED QUALITY OUT:

Audio SNR
Perceptive audio quality
Bit-error rate
Packet-error rate
etc.

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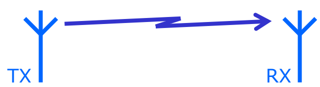
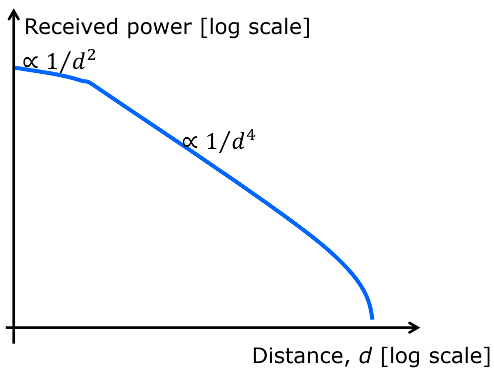
THE RADIO CHANNEL
Path loss





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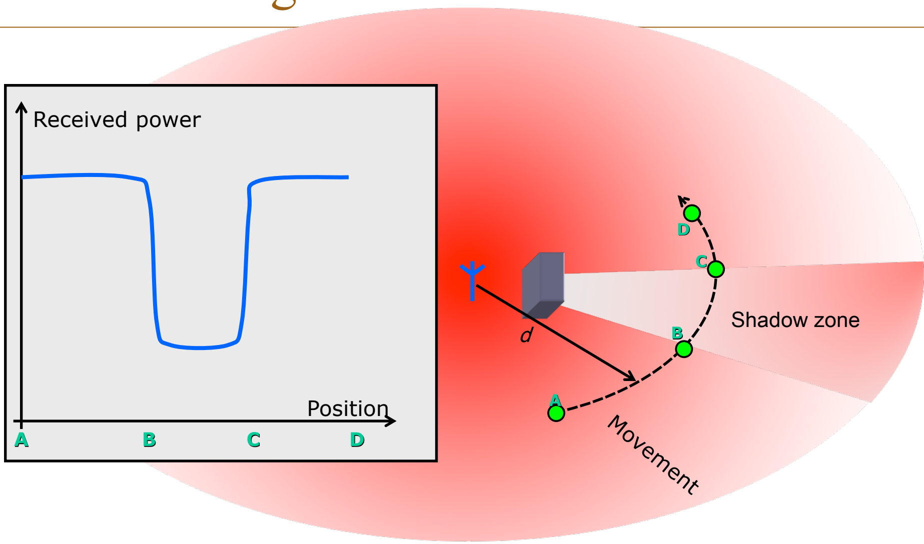
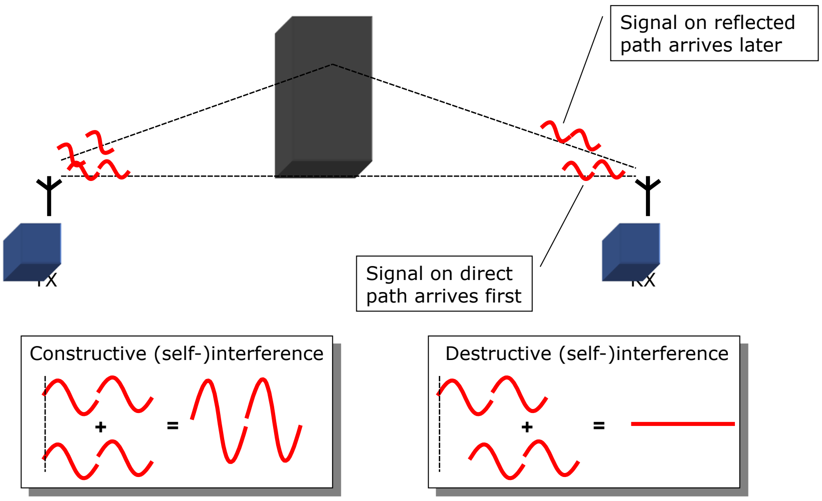
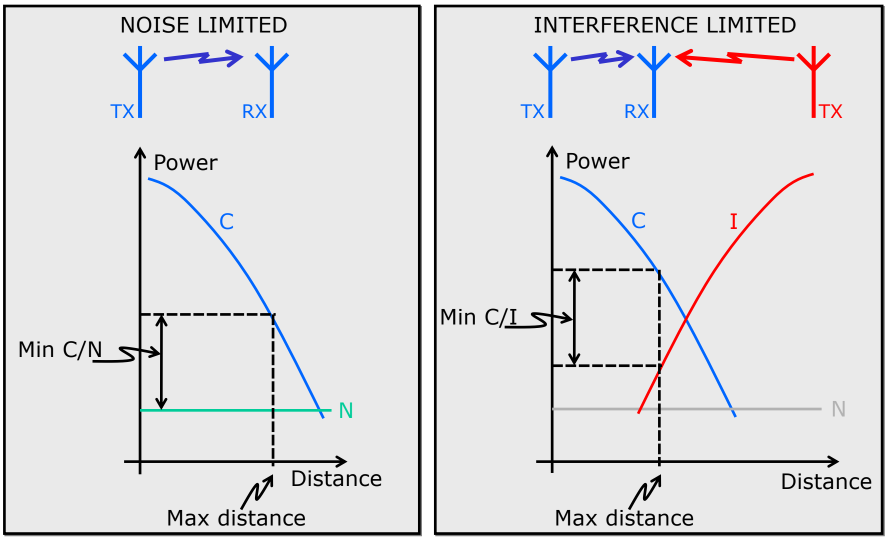
THE RADIO CHANNEL
Large-scale fading



THE RADIO CHANNEL
Small-scale fading



LINK LIMITATIONS
Noise and interference limited links



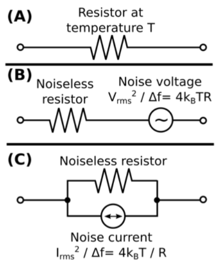
Noise

- Johnson-Nyquist noise
- Physical review 1928

- $V_{rms}^2 = 4kTBR$

- k : Bolzmann’s constant
- T : absolute temperature
- B : bandwidth
- R : Resistance

- P=4kTB



Standard noise temperature

- We set a standard temperature of 290 K for noise calculations
- 290 K = 16.85 C (“Room temperature”)
-
- Calculate noise in 1 Hz bandwith:
- P = kTB = $1.38x10^{-23}$ x 290 x 1 = 4 x 10^{-21} W = -174 dBm
- (Exact answer -173.975188679)
- P = -204 dBW

- Noise in 1kHz Bandwidth: -144 dBm

Noise factor and noise figure

- Noise figure NF = 10 log (Noise factor F)

- $F=N_{out}/kT_0G$

- $(S/N)_{out}$ = (S/N)in + NF at 290 K

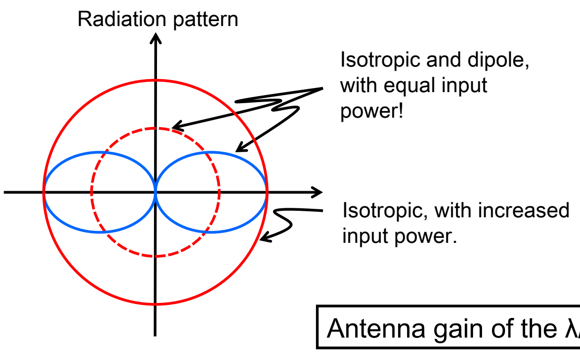
Cascade formule

- Total noise factor of a system:
- $F_T = F_1 + (F_2-1)/G_1 + (F_3-1)/G_1G_2 + \ldots + (F_N-1)/(G_1G_2\ldots G_{N-1})$
- Noise factor of a amplifier: look it up
- Noise factor of a loss at 290K: L=NF

Antenna gain (principle)

Antenna gain is a relative measure.

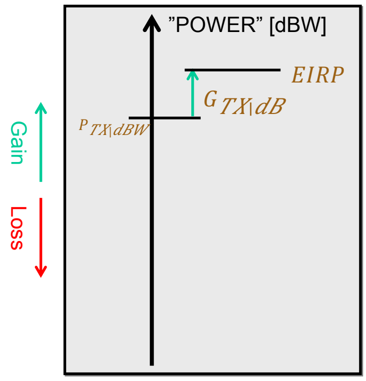
We will use the isotropic antenna as the reference.



The increase of input power to the isotropic antenna, to obtain the same maximum radiation is called the **antenna gain**!

Antenna gain of the $\lambda/2$ dipole is **2.15 dBi**.

EIRP and the link budget



$$EIRP|_{dBW} = P_{TX|dBW} + G_{TX|dB}$$

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Free-space loss Validity - the Rayleigh distance

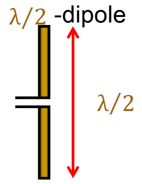
The free-space loss calculations are only valid in the **far field** of the antennas.

Far-field conditions are assumed "**far beyond"** the Rayleigh distance:

$$d_R = 2\frac{{L_a}^2}{\lambda}$$

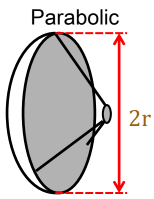
where L_a is the largest dimesion of the antenna.

Another rule of thumb is:
"**At least** N wavelengths"



$L_a = \lambda/2$

$d_R = \lambda/2$



$L_a = 2r$

$d_R = \frac{8r^2}{\lambda}$

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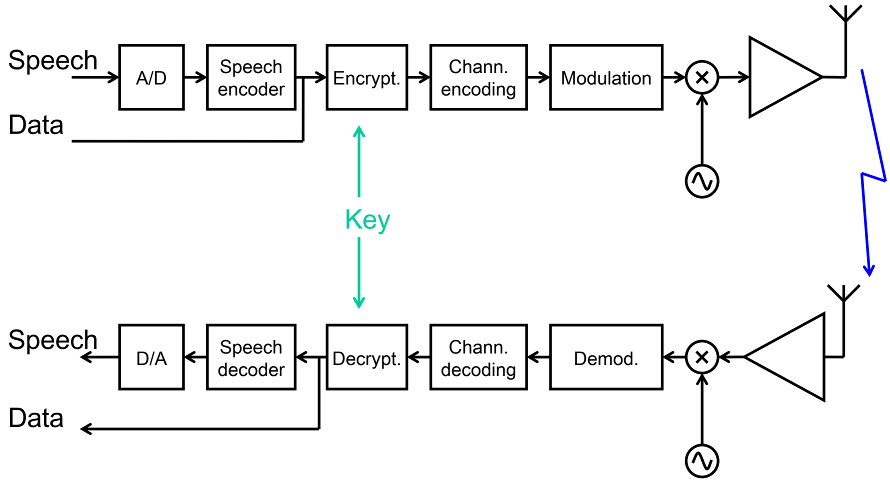
A simple structure



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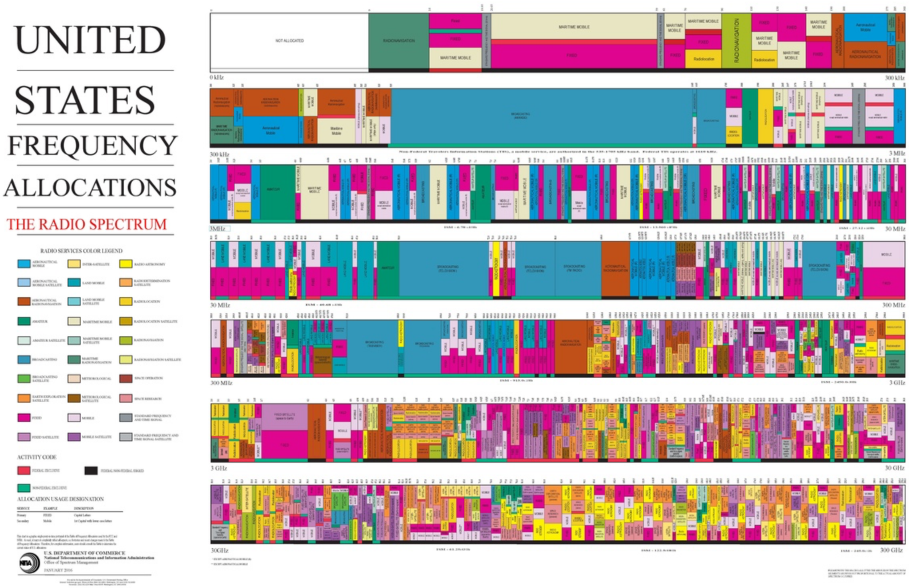
Frequency spectrum



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Bandwidth

- Shannon-Hartley Theorem
- $C = B \mathbf{x} \log_2(1+S/N)$
- The capacity of a communication link is linearly dependent on the bandwidth(B), and logarithmically on the signal to noise level(S/N).

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Classic modulation formats

Analog formats

- On-Off keying
- Amplitude modulation
- Frequency modulation

Digital formats

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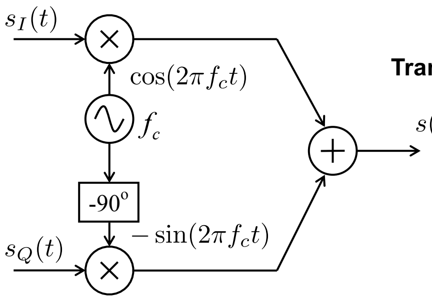
The IQ modulator

I-channel
(in-phase)

Q-channel
(quadrature)



Transmited radio signal

$$s(t) = s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)$$

Take a step into the complex domain:

Complex envelope $\tilde{s}(t) = s_I(t) + js_Q(t)$

Carrier factor $e^{j2\pi f_c t}$

⇨ $s(t) = \mathrm{Re}\{\tilde{s}(t)e^{j2\pi f_c t}\}$

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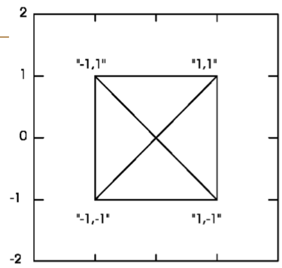
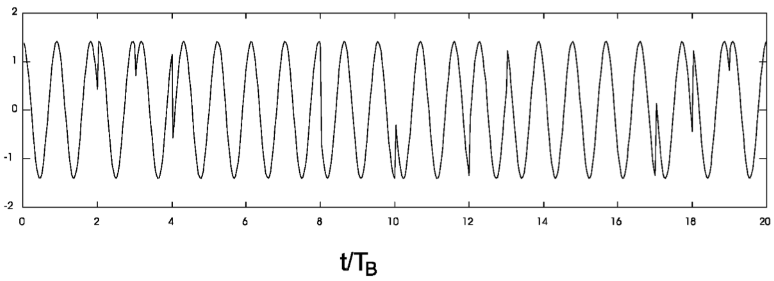
Quaternary PSK (QPSK or 4-PSK) Rectangular pulses

Complex representation



Radio signal



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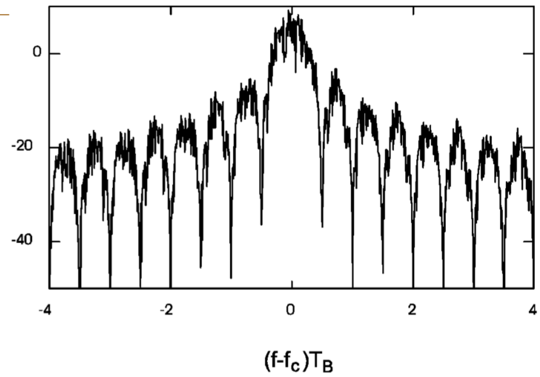
Quaternary PSK (QPSK or 4-PSK)
Rectangular pulses

Power spectral density for QPSK



Contained percentage of total energy	spectral efficiency
90%	$1,18 Bit/s/Hz$
99%	$0.10 Bit/s/Hz$

Twice the spectrum efficiency of BPSK (with rect. pulses). TWO bits/pulse instead of one.

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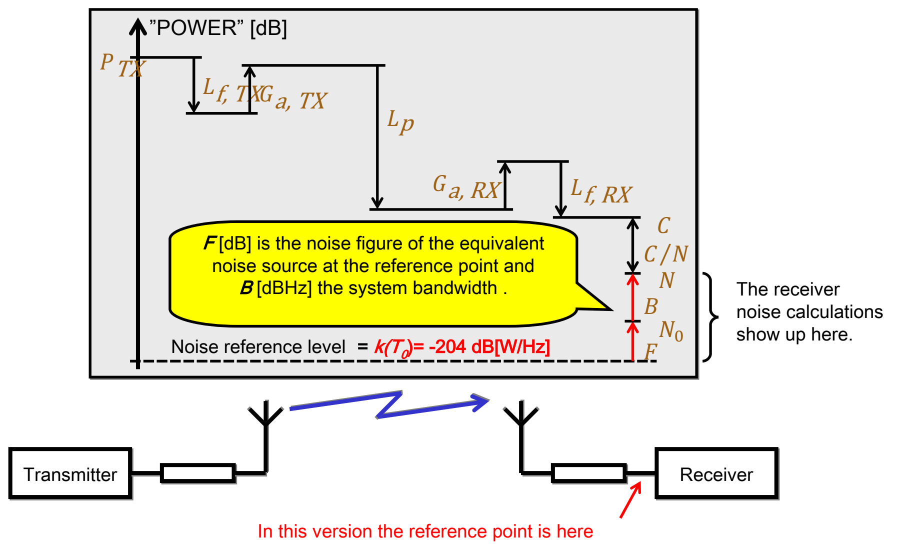
Receiver noise
The link budget



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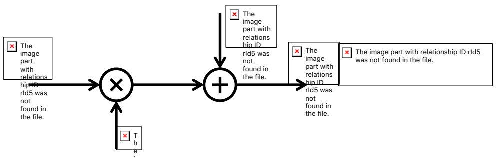
Optimal receiver
The AWGN channel

The additive white Gaussian noise (AWGN) channel



- transmitted signal
- channel attenuation
- white Gaussian noise
- received signal

In our digital transmission system, the transmitted signal $s(t)$ would be one of, let's say M, different alternatives $s_0(t)$, $s_1(t)$, … , $s_{M-1}(t)$.

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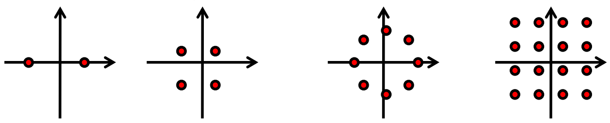
Optimal receiver
Bit-error rates (BER)

EXAMPLES:	2PAM	4QAM	8PSK	16QAM
Bits/symbol	1	2	3	4
Symbol energy	E_b	$2E_b$	$3E_b$	$4E_b$
BER	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$	$\sim\frac{2}{3}Q\left(\sqrt{0.87\frac{E_b}{N_0}}\right)$	$\sim\frac{3}{2}Q\left(\sqrt{\frac{E_{b,\,max}}{2.25N_0}}\right)$



Gray coding is used when calculating these BER.

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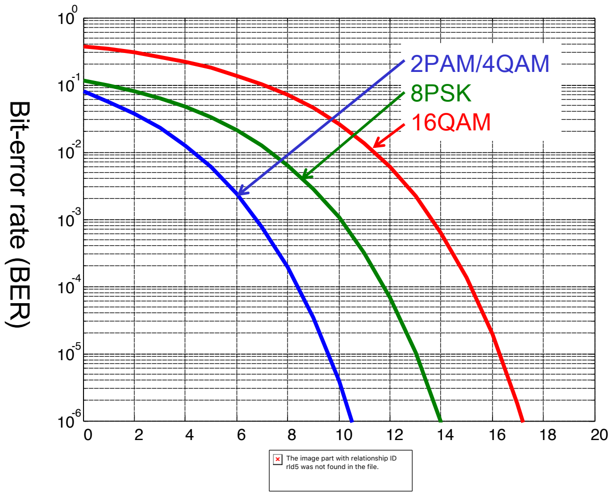
Optimal receiver
Bit-error rates (BER), cont.



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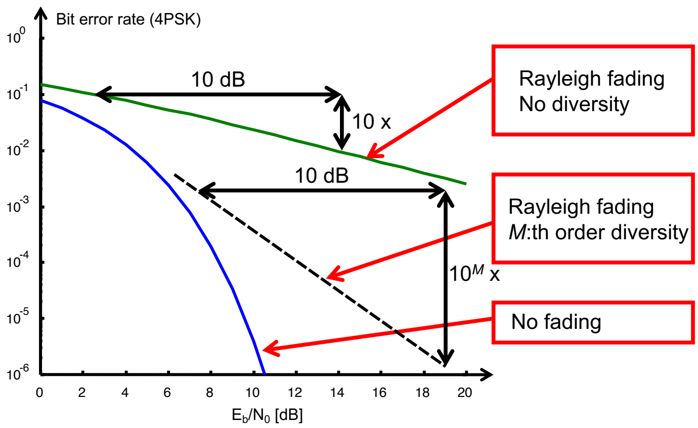
Diversity arrangements
General improvement trend



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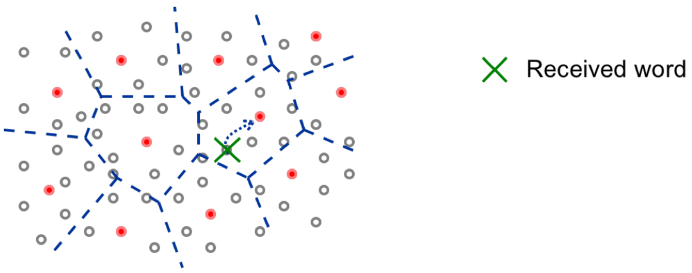
Channel coding
Illustration of decoding

If we receive a sequence that is not a valid code word, we decode to the **closest** one.



Using this "rule" we can create decision boundaries like we did for signal constellations.

One thing remains ... what do we mean by **closest**?
We need a distance measure!

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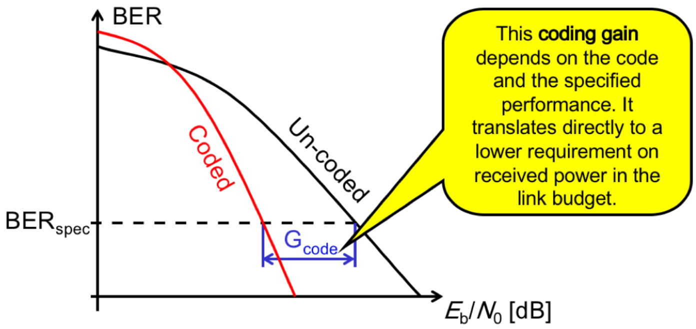
Channel coding
Coding gain

When applying channel codes we decrease the E_b/N_0 required to obtain some specified performance (BER).



NOTE: E_b denotes **energy per information bit**, even for the coded case.

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Channel coding
Linear block codes

The encoding process of a linear block code can be written as

$$\boldsymbol{x} = \boldsymbol{G}\boldsymbol{u}$$

where

$\boldsymbol{u}$ k - dimensional information vector

$\boldsymbol{G}$ n x k - dimensional generator matrix

$\boldsymbol{x}$ n - dimensional code word vector

The matrix calculations are done in an appropriate arithmetic.
We will primarily assume **binary codes** and **modulo-2** arithmetic.

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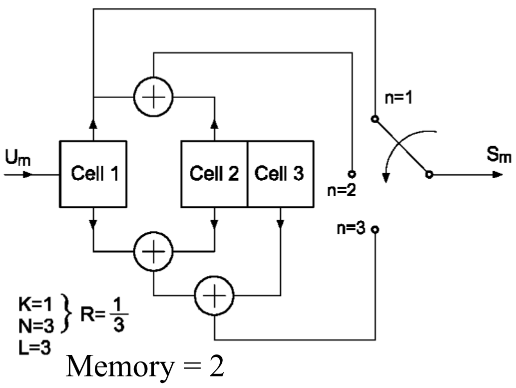
Channel coding
Encoding example



Input	State	Output	Next state
0	00	000	00
1	00	111	10
0	01	001	00
1	01	110	10
0	10	011	01
1	10	100	11
0	11	010	01
1	11	101	11

We usually start the encoder in the **all-zero** state!

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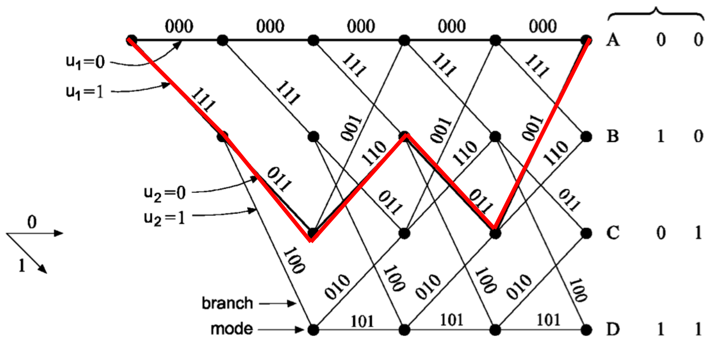
Channel coding
Encoding example, cont.

We can view the encoding process in a trellis created from the table on the previous slide.

Input (information) bit sequence	1	0	1	0	0
Output (coded) bit sequence	111	011	110	011	001



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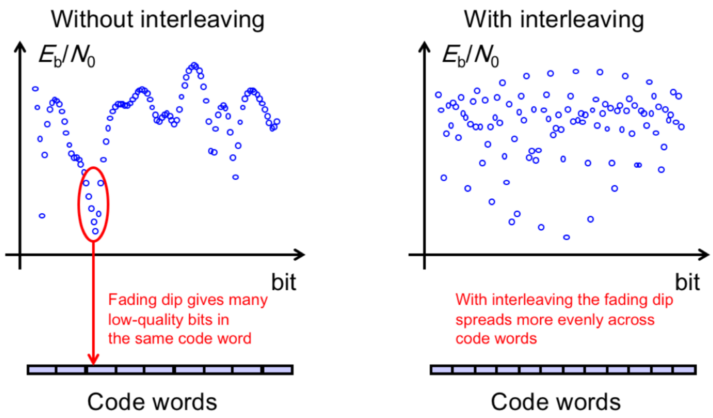
Channel coding
Distribution of low-quality bits



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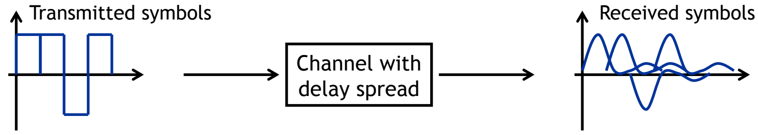
Inter-symbol interference
Background

Even if we have designed the basis pulses of our modulation to be interference free in time, i.e. no leakage of energy between consecutive symbols, multi-path propagation in our channel will cause a delay-spread and **inter-symbol interference (ISI)**.



ISI will degrade performance of our receiver, unless mitigated by some mechanism. This mechanism is called an **equalizer**.

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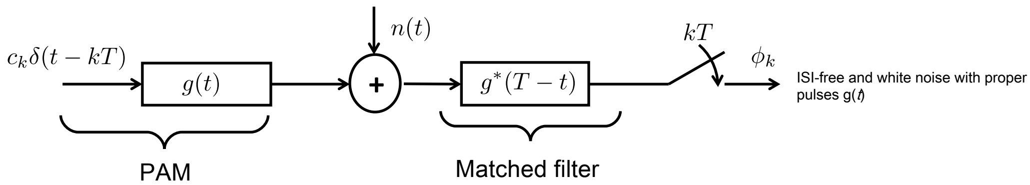
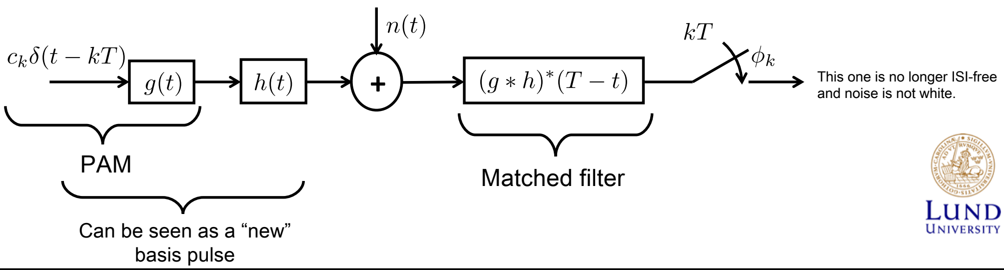
Including a channel impulse response

What we have used so far (PAM and optimal receiver):



Including a channel impulse response $h(t)$:



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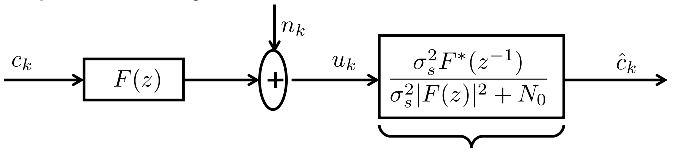
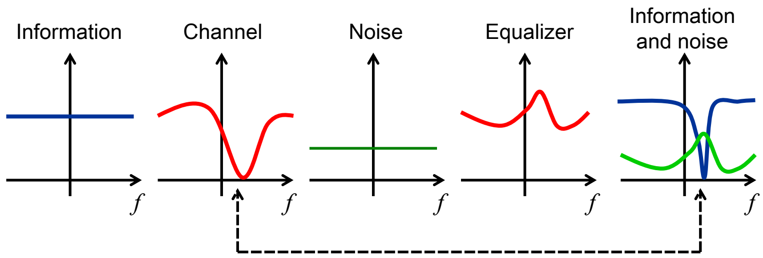
Mean Square Error equalizer

The **MSE equalizer** is designed to minimize the error variance

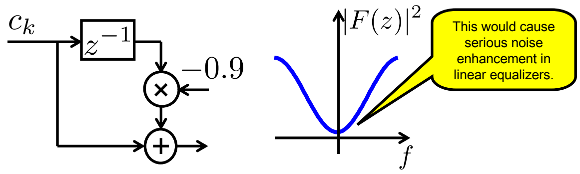




The Viterbi-equalizer

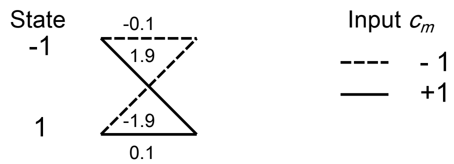
Let's use an example to describe the **Viterbi-equalizer**.

Discrete-time channel:



Further, assume that our symbol alphabet is –1 and +1 (representing the bits 0 and 1, respectively).

The fundamental trellis stage:



The Viterbi-equalizer

The Viterbi-equalizer (detector) is optimal in terms of minimizing the probability of detecting the wrong sequence of symbols.

For transmitted sequences of length N over a length L+1 channel, it reduces the brute-force maximum-likelihood detection complexity of 2^N comparisons to N stages of 2^L comparisons through elimination of trellis paths. L is typically MUCH SMALLER than N.

Even if it reduces the complexity considerably (compared to brute-force ML) it can have a too high complexity for practical implementations if the length of the channel (ISI) is large.

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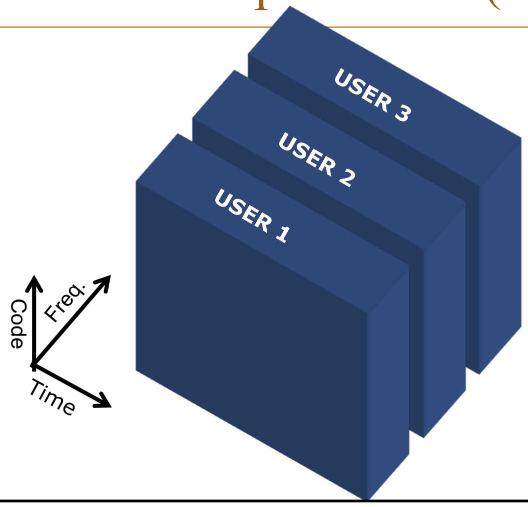
MULTIPLE ACCESS
Freq.-division multiple access (FDMA)



Users are separated in frequency bands.

Examples: Nordic Mobile Telephony (NMT), Advanced Mobile Phone System (AMPS)

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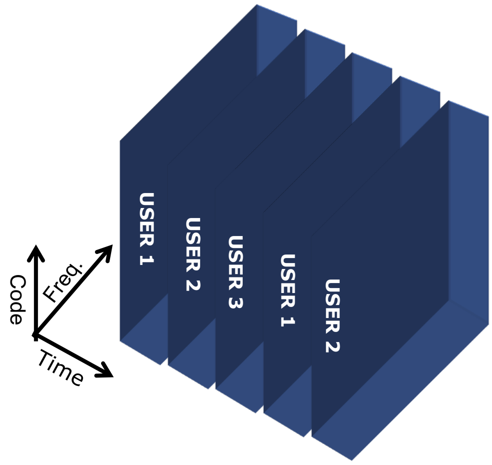
MULTIPLE ACCESS
Time-division multiple access (TDMA)



Users are separated in time slots.

Example: Global System for Mobile communications (GSM)

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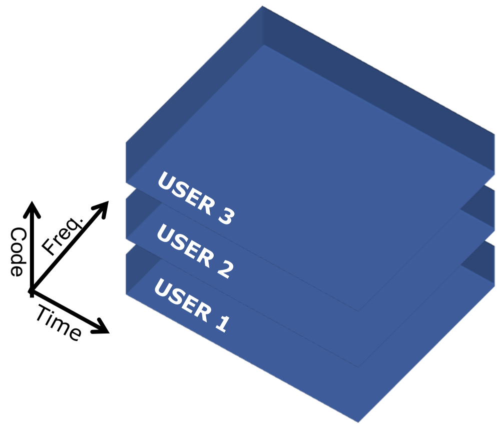
MULTIPLE ACCESS
Code-division multiple access (CDMA)



Users are separated by spreading codes.

Examples: CdmaOne, Wideband CDMA (WCDMA), Cdma2000

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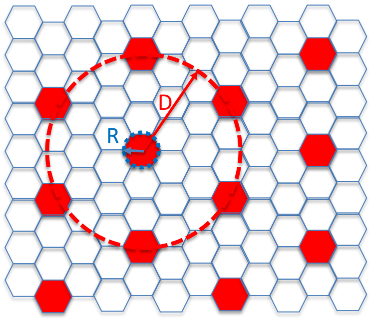
Interference and spectrum efficiency
Cellular systems

Let us assume that we have a cellular system with a regular hexagonal cell structure.



The radius of a cell is *R*.

The distance to the closest co-channel base-stations (first tier) is *D*.

To achieve this reuse ratio *D*/*R*, we need to split the available radio resource into

$$N_{cluster} = \frac{(D/R)^2}{3}$$

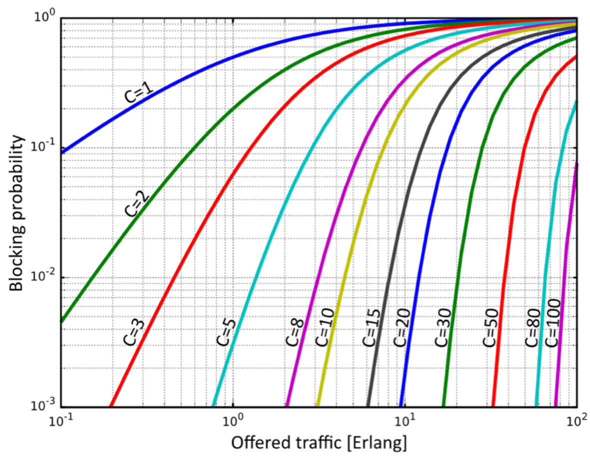
shares and split them among an equal number of base stations.

Note: Only certain *D*/*R* will result in useful cluster sizes.

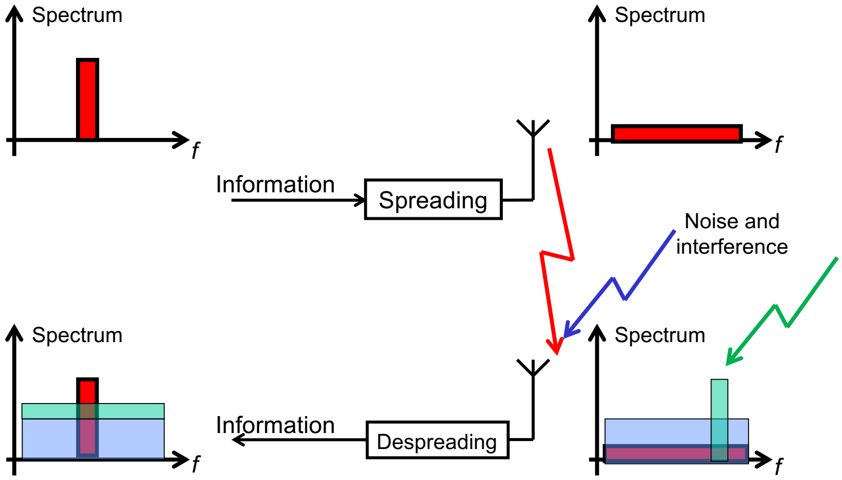
Interference and spectrum efficiency

Erlang-B

Relation between blocking probability and offered traffic for different number of available speech channels in a cell.



Spread Spectrum Techniques



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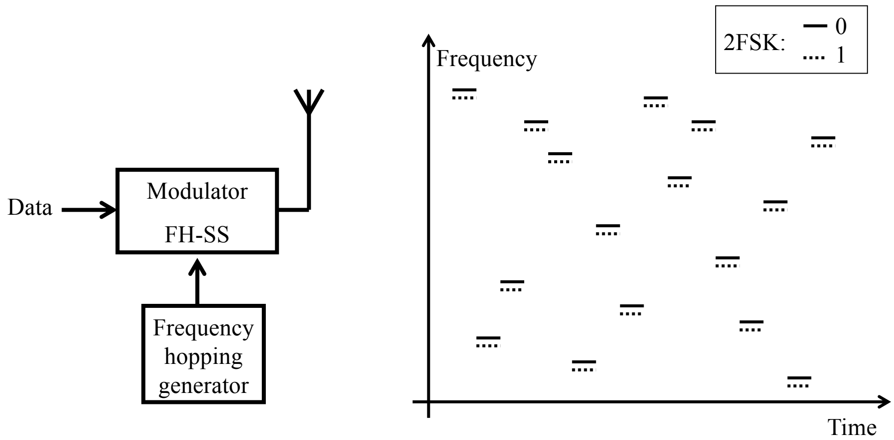
Frequency-Hopping Spread Spectrum



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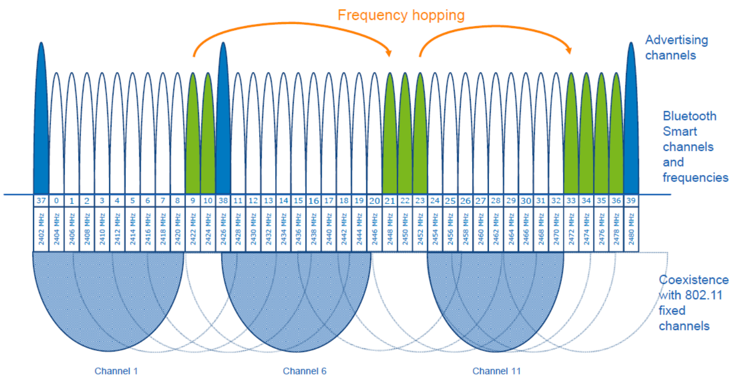
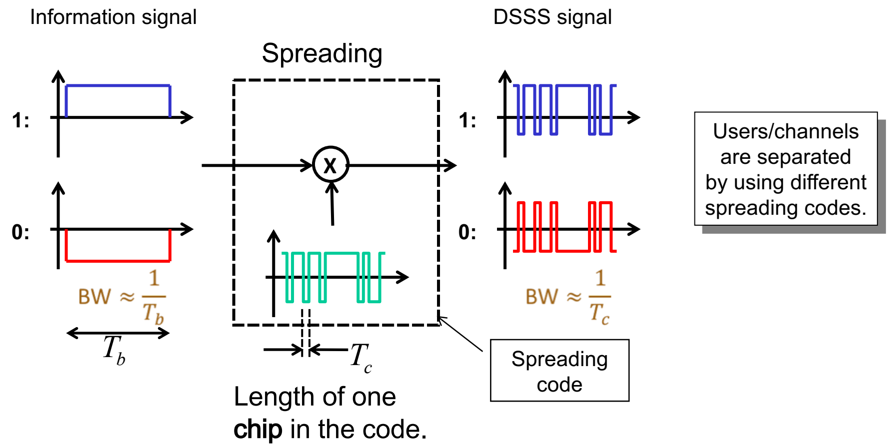
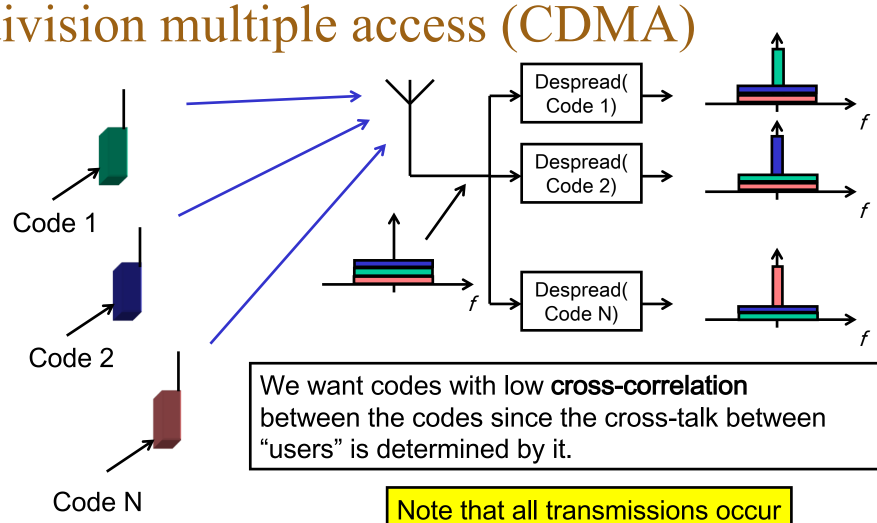
Adaptive frequency hopping



Direct-Sequence Spread Spectrum DSSS



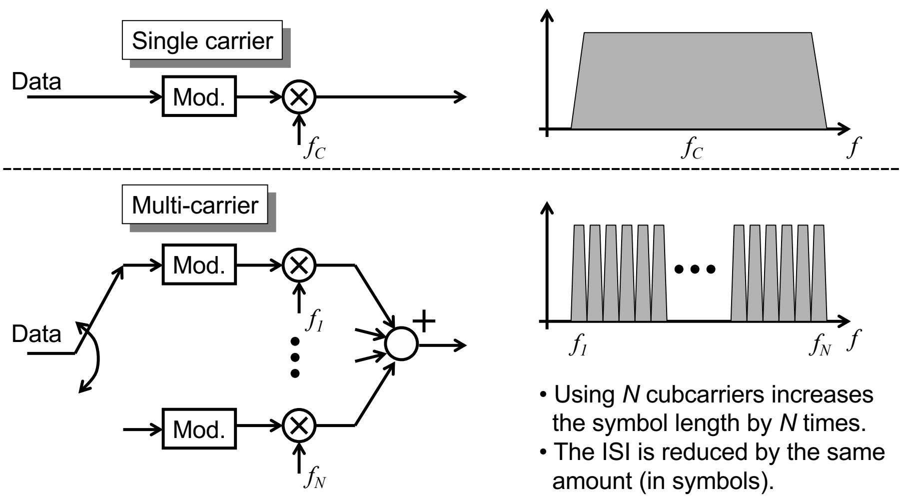
Code-division multiple access (CDMA)



We want codes with low **cross-correlation** between the codes since the cross-talk between "users" is determined by it.

Note that all transmissions occur within the same bandwidth!

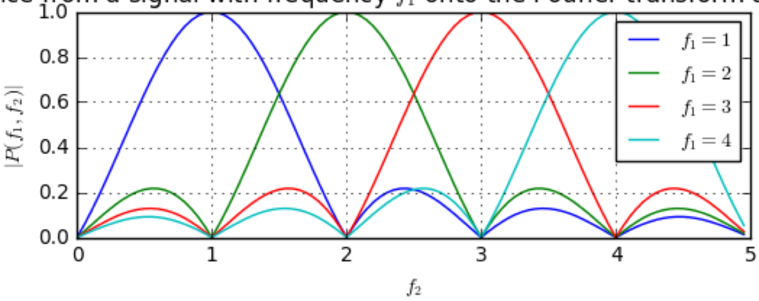
Single/Multi-carrier



- Using N cubcarriers increases the symbol length by N times.
- The ISI is reduced by the same amount (in symbols).

OFDM
Orthogonal Frequency-Division Multiplexing

Interference from a signal with frequency f_1 onto the Fourier transform at frequency f_2.



http://dspillustrations.com/pages/posts/misc/intuitive-explanation-of-ofdm.html

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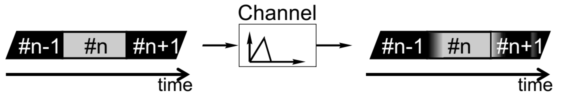
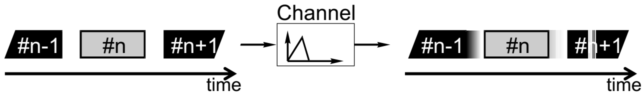
Addition of guard intervals and cyclic prefix

1980's: Improved digital circuits increses interest

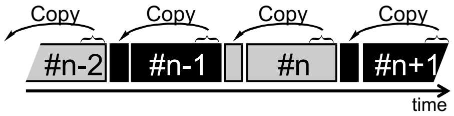
No guard interval => Interference between both subcarriers and symbols



Guard interval => No interference between symbols



Cyclic prefix => No interference between neither subcarriers nor symbols



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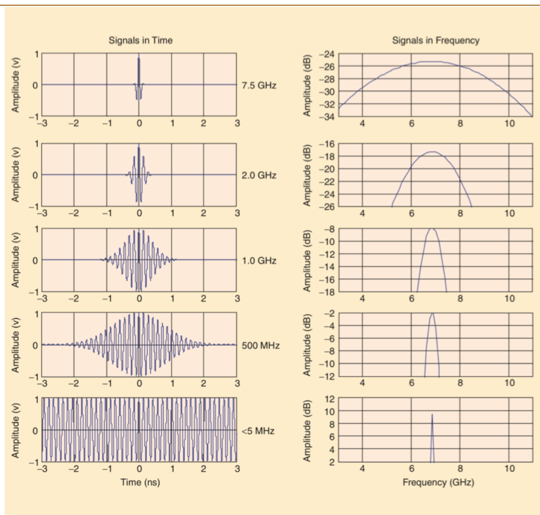
Signal bandwidth



Ultra-Wideband Wireless Systems, Aiello and Rogerson, IEEE Microwave Magazine

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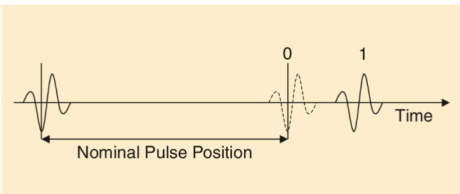
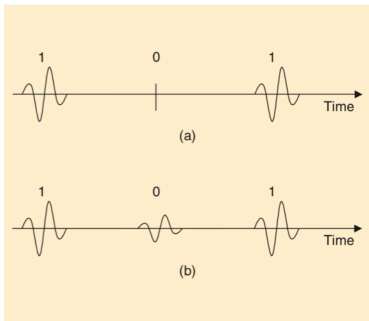
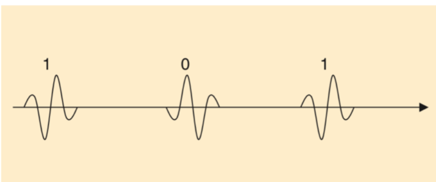
Pulse Position Modulation (PPM),
Pulse Amplitude Modulation (PAM), Bi-phase Modulation







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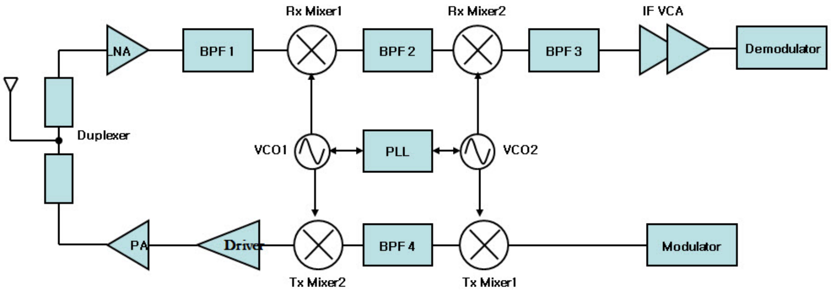
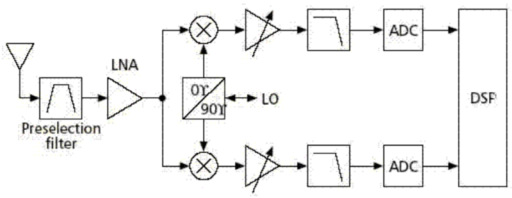
Radio architectures: Double Super Heterodyne



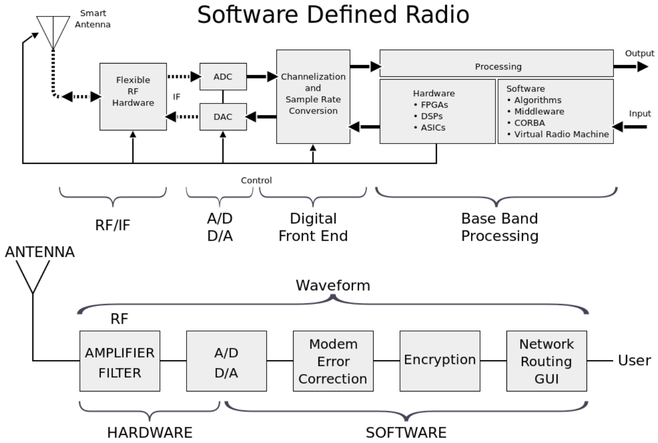
Homodyne

- Direct conversion
- Zero-IF
- Synchrodyne
- (Very low IF)



Software radio - SDR

- Wikipedia picture

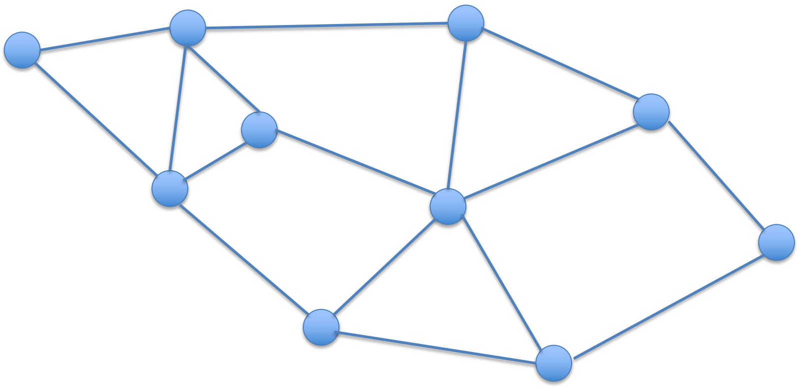


Cognitive radio

- ”A Cognitive Radio (CR) is an intelligent radio that can be programmed and configured dynamically. Its transceiver is designed to use the best wireless channels in its vicinity. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location. This process is a form of dynamic spectrum management.”

www.netmanias.com/en/post/blog/10813/5g-new-radio/cognitive-radio-the-new-5g-radio

Relaying, multi-hop, Cooperative communication



Source coding

- Source coding **removes** redundancy from the information to be transmitted.
  - Similar to compression.
- Channel coding **adds** redundancy to the information to be transmitted.
- Both steps are useful, as there is a difference in the type of redundancy that is most effective.

Wireless system design

- Problem: Move information (data) from point A to B.
- Examples of design questions:
  - What kind of information? (Quality of Service)
  - What type of signal? (source coding)
  - How much, how fast? (Data bandwidth)
  - Environment? (Carrier frequency, RF bandwidth, modulation, equalization)
  - What type of application? (Cost, complexity)
    - » Channel coding, interleaving
    - » Diversity, Network type
  - How far? (TX Power, antennas, RX Noise Factor)

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