

RADIO SYSTEMS - ETIN15



Lecture no: **5**

Digital modulation

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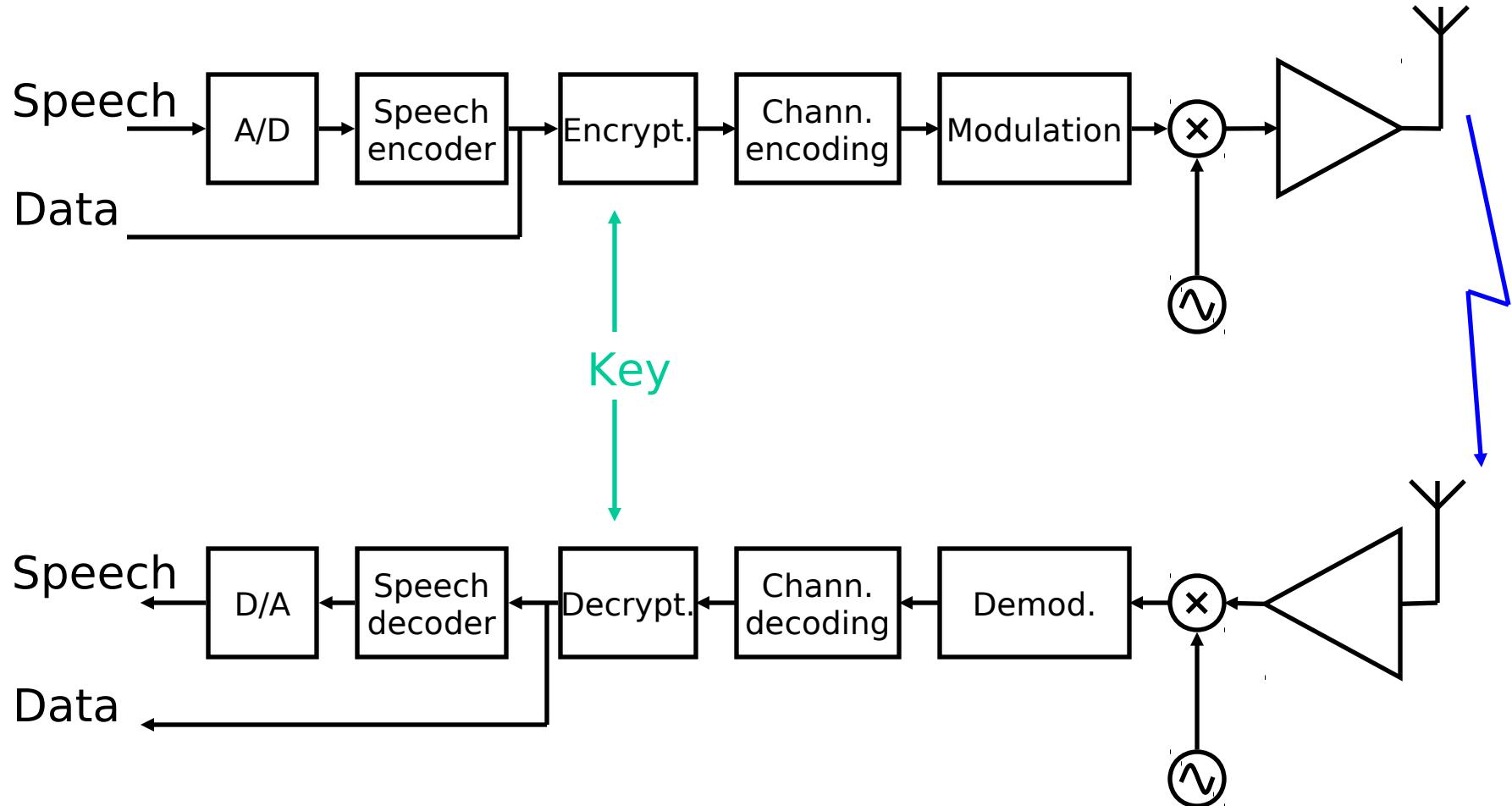
Contents

- Brief overview of a wireless communication link
- Radio signals and complex notation (again)
- Modulation basics
- Important modulation formats



STRUCTURE OF A WIRELESS COMMUNICATION LINK

A simple structure



(Read Chapter 10 for more details)



RADIO SIGNALS AND COMPLEX NOTATION

(from Lecture 3)



Simple model of a radio signal

- A transmitted radio signal can be written

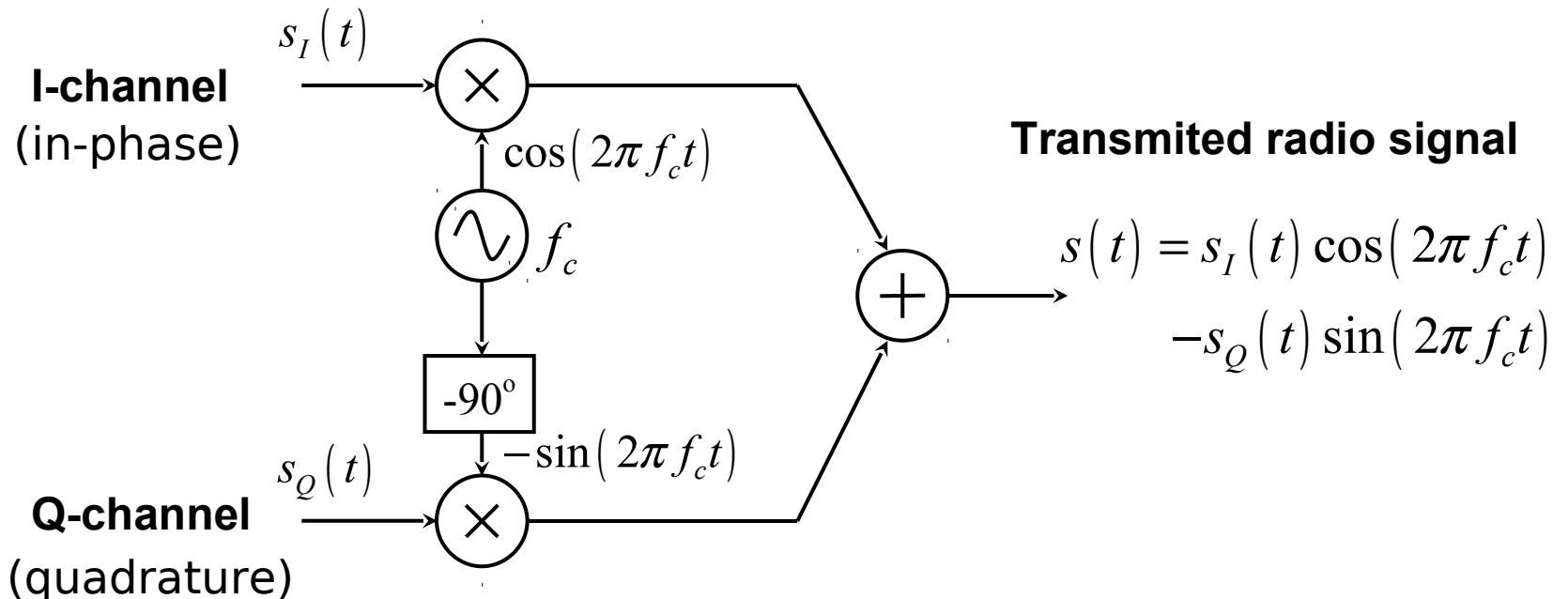
$$s(t) = A \cos(2\pi ft + \phi)$$

↑ ↑ ↑
Amplitude Frequency Phase

- By letting the transmitted information change the amplitude, the frequency, or the phase, we get the three basic types of digital modulation techniques
 - **ASK** (Amplitude Shift Keying)
 - **FSK** (Frequency Shift Keying)
 - **PSK** (Phase Shift Keying)
- Constant amplitude



The IQ modulator



Take a step into the complex domain:

$$\text{Complex envelope } \tilde{s}(t) = s_I(t) + j s_Q(t)$$

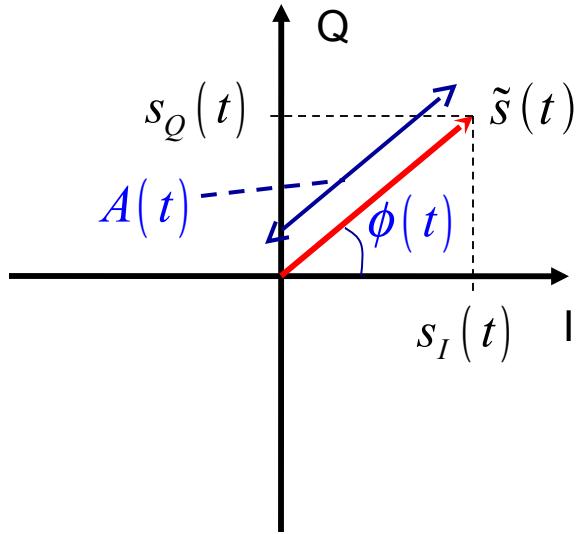
$$\rightarrow s(t) = \text{Re} \{ \tilde{s}(t) e^{j 2\pi f_c t} \}$$

Carrier factor $e^{j 2\pi f_c t}$



Interpreting the complex notation

Complex envelope (phasor)



Transmitted radio signal

$$\begin{aligned} s(t) &= \operatorname{Re}\{\tilde{s}(t)e^{j2\pi f_c t}\} \\ &= \operatorname{Re}\{A(t)e^{j\phi(t)}e^{j2\pi f_c t}\} \\ &= \operatorname{Re}\{A(t)e^{j(2\pi f_c t + \phi(t))}\} \\ &= A(t)\cos(2\pi f_c t + \phi(t)) \end{aligned}$$

Polar coordinates:

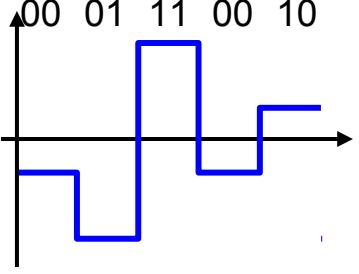
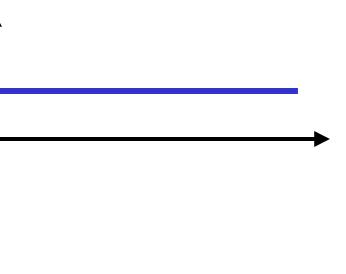
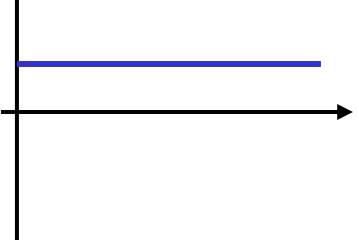
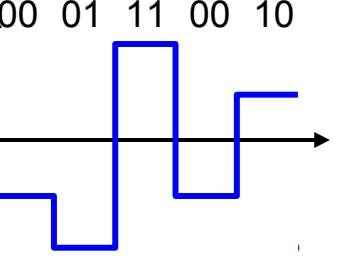
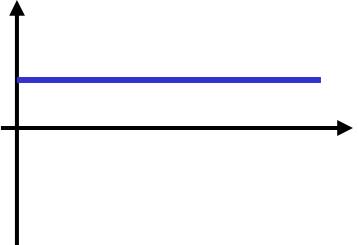
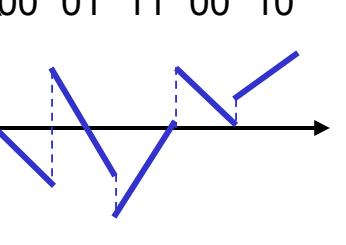
$$\tilde{s}(t) = s_I(t) + j s_Q(t) = A(t) e^{j\phi(t)}$$

By manipulating the amplitude $A(t)$ and the phase $\Phi(t)$ of the complex envelope (phasor), we can create any type of modulation/radio signal.

Example: Amplitude, phase and frequency modulation



$$s(t) = A(t) \cos(2\pi f_c t + \phi(t))$$

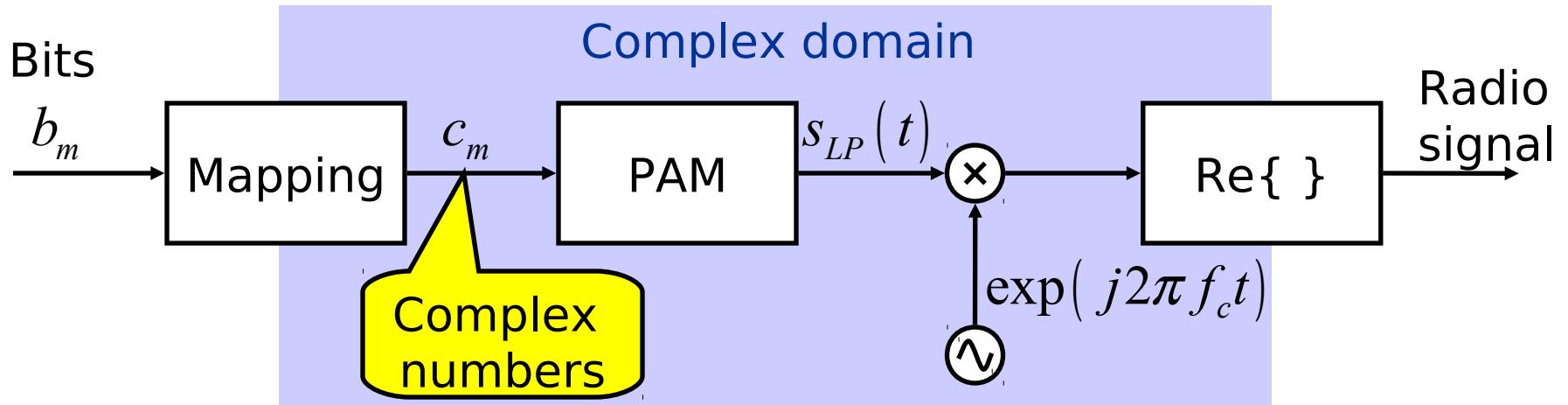
	$A(t)$	$\phi(t)$	Comment:
4ASK			<ul style="list-style-type: none">- Amplitude carries information- Phase constant (arbitrary)
4PSK			<ul style="list-style-type: none">- Amplitude constant (arbitrary)- Phase carries information
4FSK			<ul style="list-style-type: none">- Amplitude constant (arbitrary)- Phase slope (frequency) carries information



MODULATION BASICS

Pulse amplitude modulation (PAM)

The modulation process



$$\text{PAM: } s_{LP}(t) = \sum_{m=-\infty}^{\infty} c_m g(t - m T_s)$$

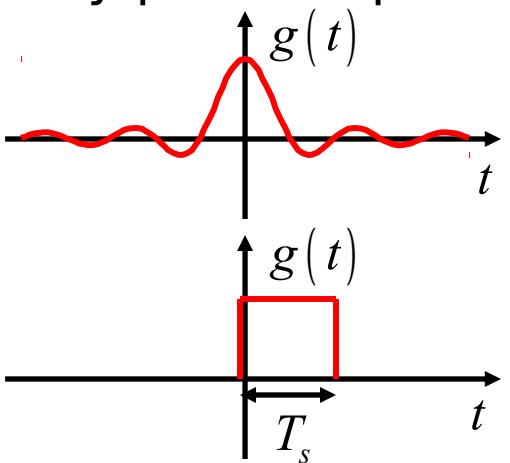
Symbol time

“Standard” basis pulse criteria

$$\int_{-\infty}^{\infty} |g(t)|^2 dt = 1 \text{ or } = T_s \quad (\text{energy norm.})$$

$$\int_{-\infty}^{\infty} g(t) g^*(t - m T_s) dt = 0 \text{ for } m \neq 0 \quad (\text{orthogonality})$$

Many possible pulses





Pulse amplitude modulation (PAM) Basis pulses and spectrum

Assuming that the complex numbers c_m representing the data are independent, then the **power spectral density** of the base band PAM signal becomes:

$$S_{LP}(f) \sim \left| \int_{-\infty}^{\infty} g(t) e^{-j2\pi f t} dt \right|^2$$

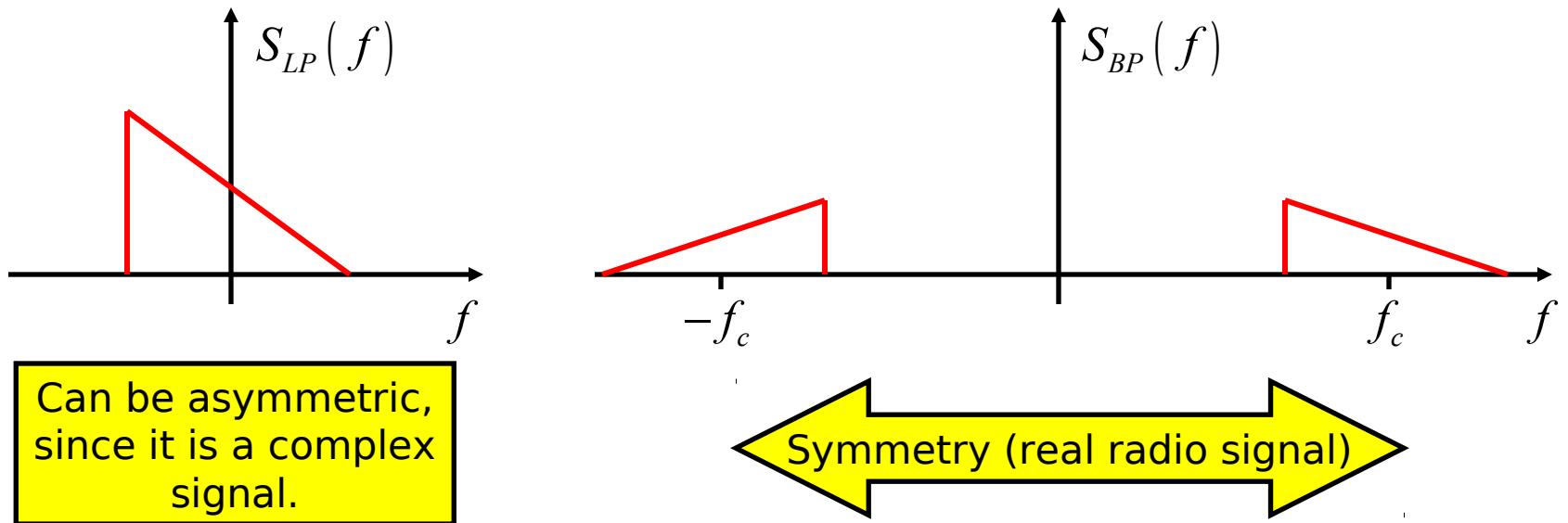
which translates into a radio signal (band pass) with

$$S_{BP}(f) = \frac{1}{2} (S_{LP}(f - f_c) + S_{LP}(-f - f_c))$$

Pulse amplitude modulation (PAM) Basis pulses and spectrum



Illustration of power spectral density of the (complex) base-band signal, $S_{LP}(f)$, and the (real) radio signal, $S_{BP}(f)$.



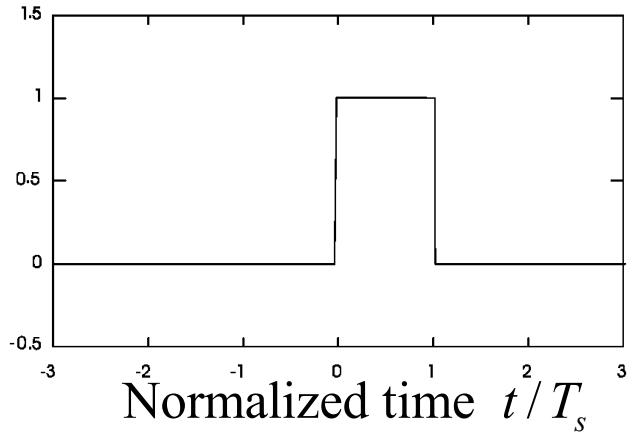
What we need are basis pulses $g(t)$ with nice properties like:

- Narrow spectrum (low side-lobes)
- Relatively short in time (low delay)

Pulse amplitude modulation (PAM) Basis pulses

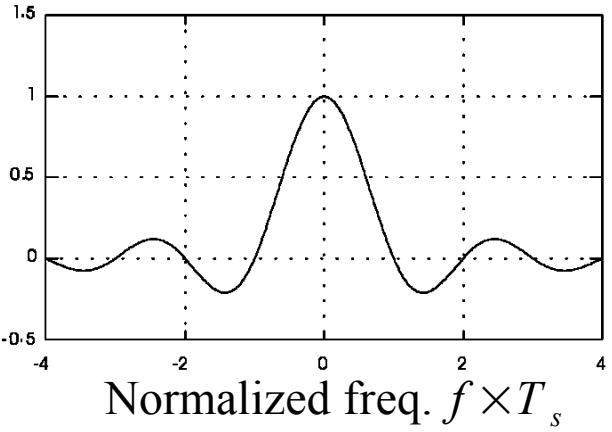


TIME DOMAIN

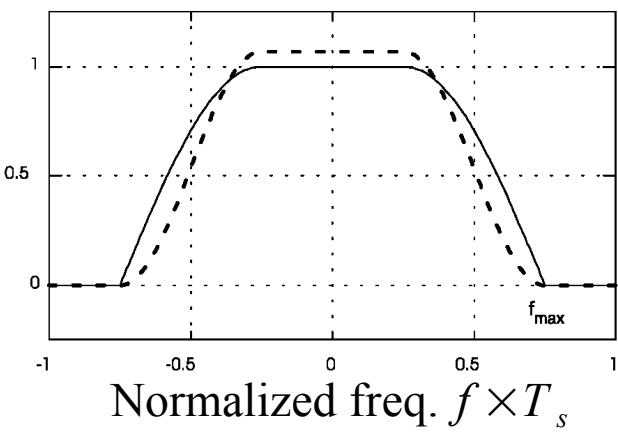
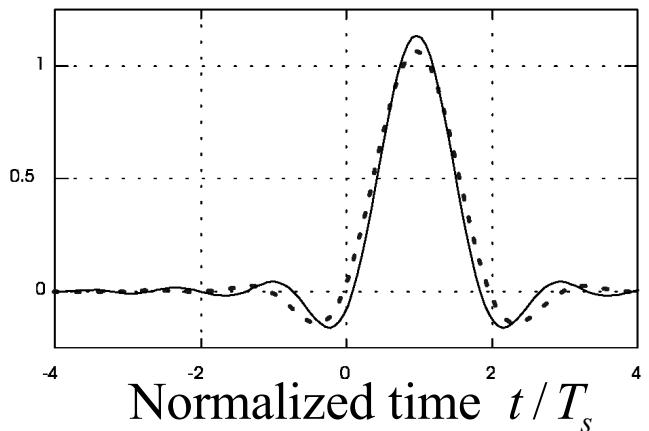


Rectangular [in time]

FREQ. DOMAIN



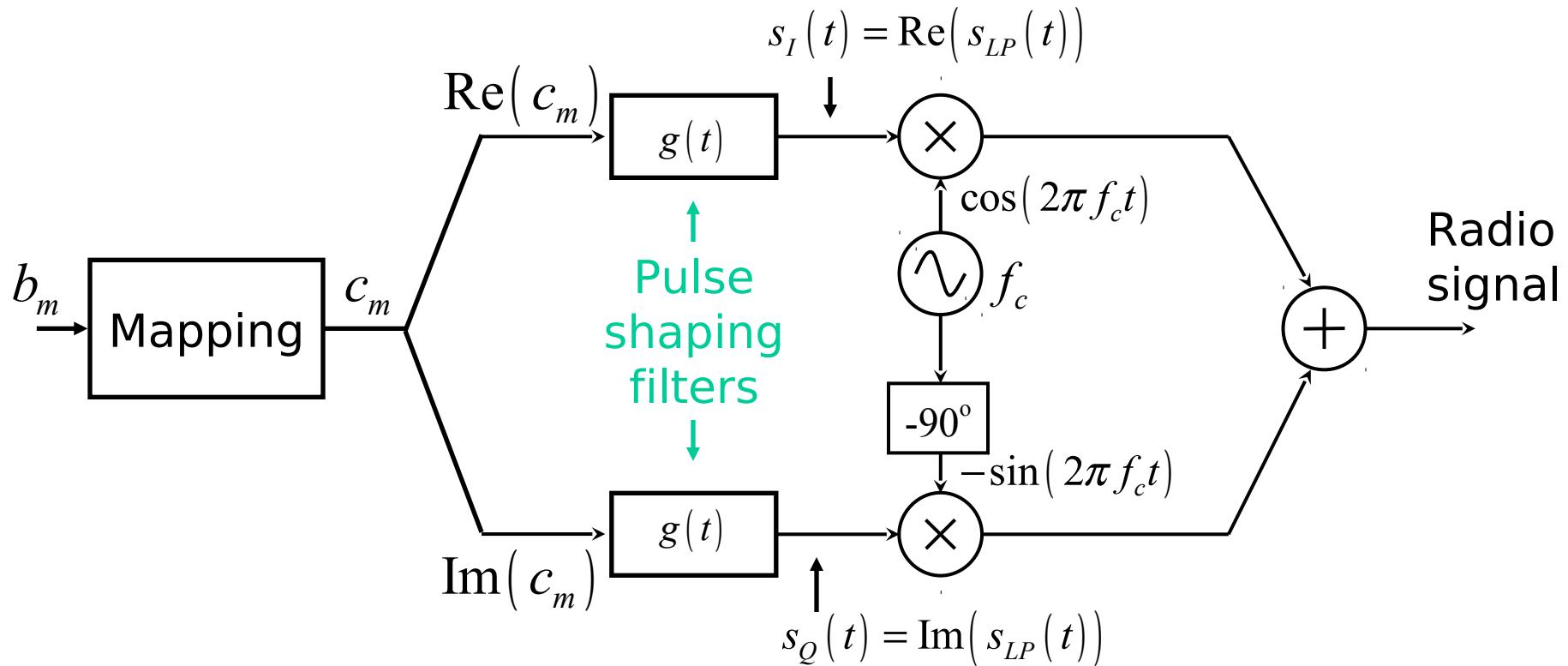
(Root-) Raised-cosine [in freq.]



Pulse amplitude modulation (PAM) Interpretation as IQ-modulator

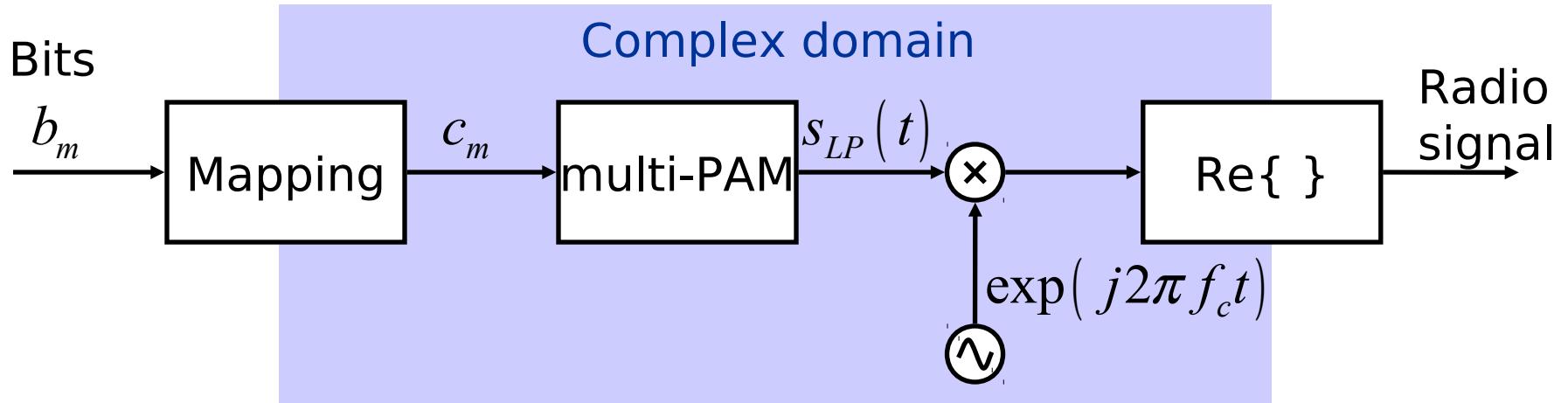


For real valued basis functions $g(t)$ we can view PAM as:



(Both the rectangular and the (root-) raised-cosine pulses are real valued.)

Multi-PAM Modulation with multiple pulses



$$\text{multi-PAM: } s_{LP}(t) = \sum_{m=-\infty}^{\infty} g_{c_m}(t - m T_s)$$

“Standard” basis pulse criteria

$$\int |g_{c_m}(t)|^2 dt = 1 \text{ or } = T_s \quad (\text{energy norm.})$$

$$\int g_{c_m}(t) g_{c_m}^*(t - kT_s) dt = 0 \text{ for } k \neq 0 \quad (\text{orthogonality})$$

$$\int g_{c_m}(t) g_{c_n}^*(t) dt = 0 \text{ for } c_m \neq c_n \quad (\text{orthogonality})$$

Several different pulses

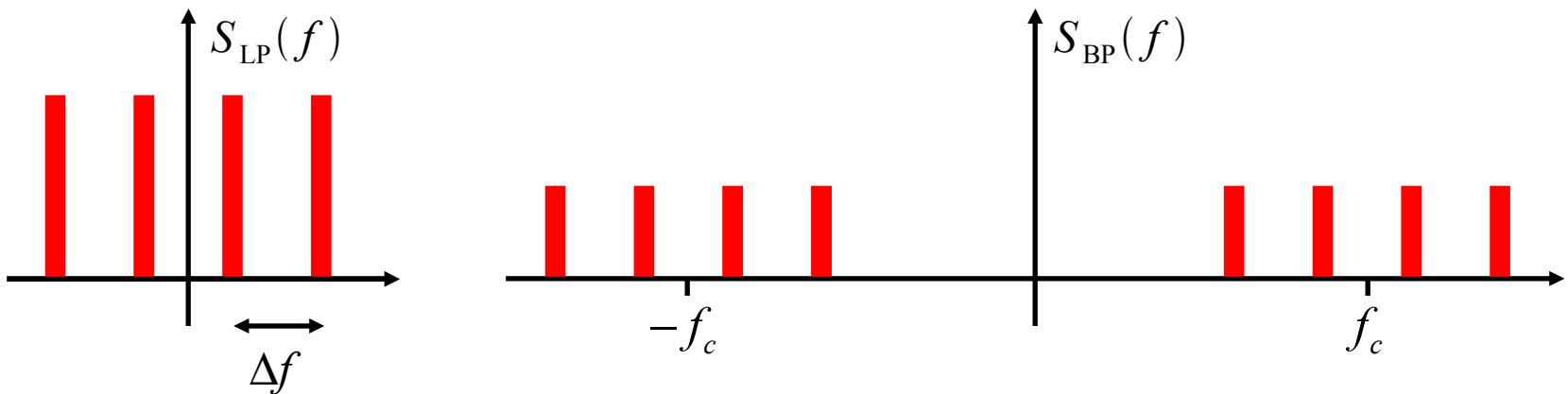
Multi-PAM Modulation with multiple pulses



Frequency-shift keying (FSK) with M (even) different transmission frequencies can be interpreted as multi-PAM if the basis functions are chosen as:

$$g_k(t) = e^{-j\pi k \Delta f t} \text{ for } 0 \leq t \leq T_s$$

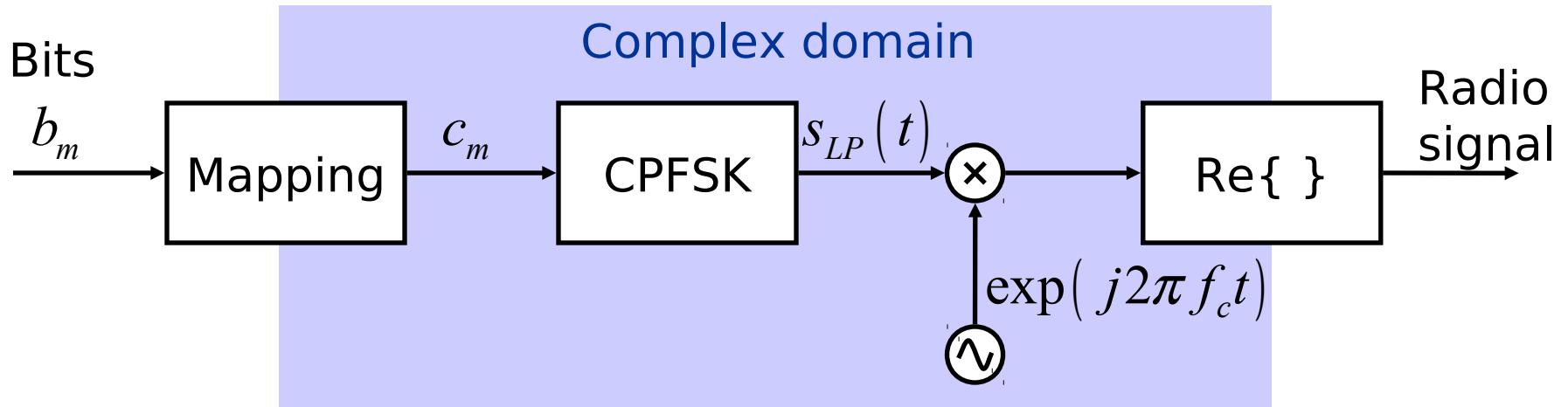
and for $k = +/- 1, +/- 3, \dots, +/- M/2$



Bits: 00 01 10 11

Continuous-phase FSK (CPFSK)

The modulation process



$$\text{CPFSK: } s_{LP}(t) = A \exp(j \Phi_{\text{CPFSK}}(t))$$

where the amplitude A is constant and the phase is

$$\Phi_{\text{CPFSK}}(t) = 2\pi h_{\text{mod}} \sum_{m=-\infty}^{\infty} c_m \int_{-\infty}^t \tilde{g}(u - mT) du$$

where h_{mod} is the modulation index.

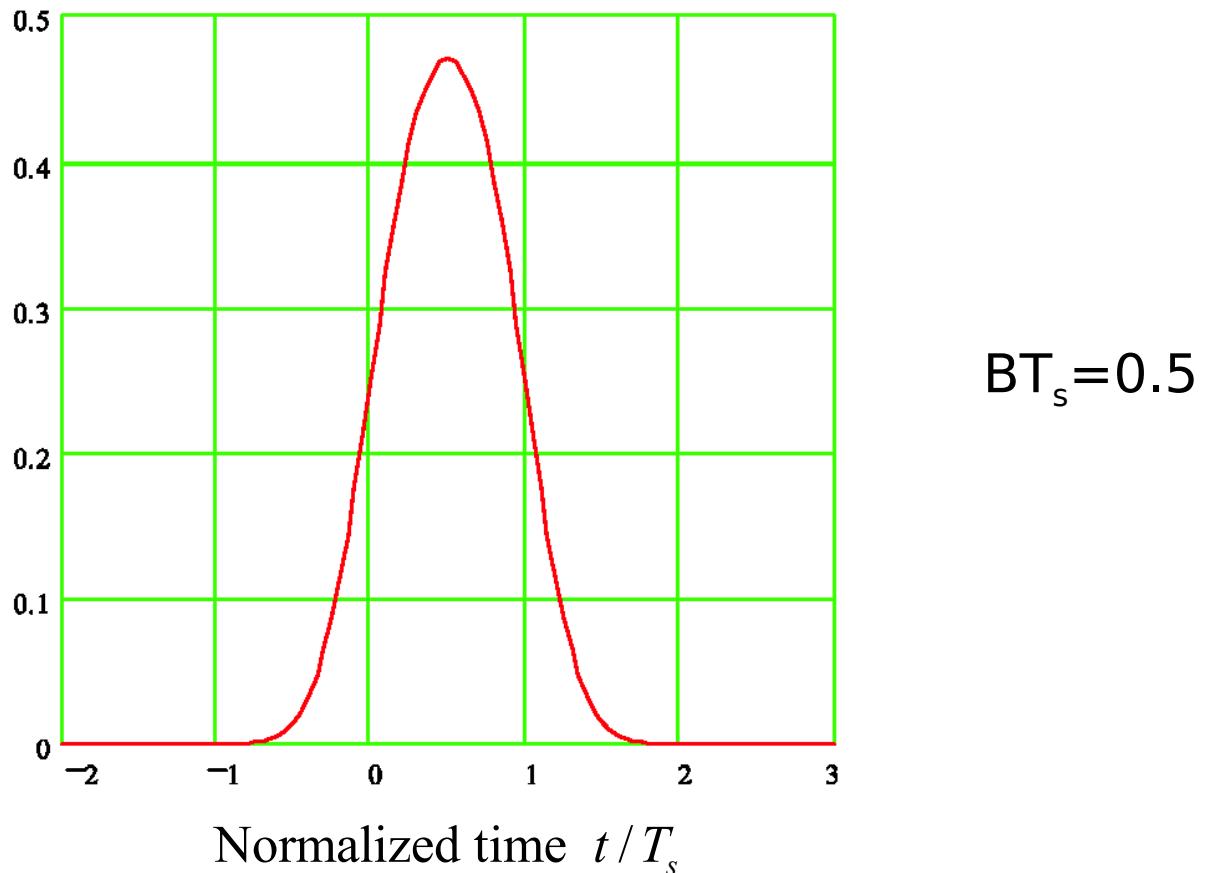
Phase basis pulse

Continuous-phase FSK (CPFSK)

The Gaussian phase basis pulse



In addition to the rectangular phase basis pulse, the Gaussian is the most common.





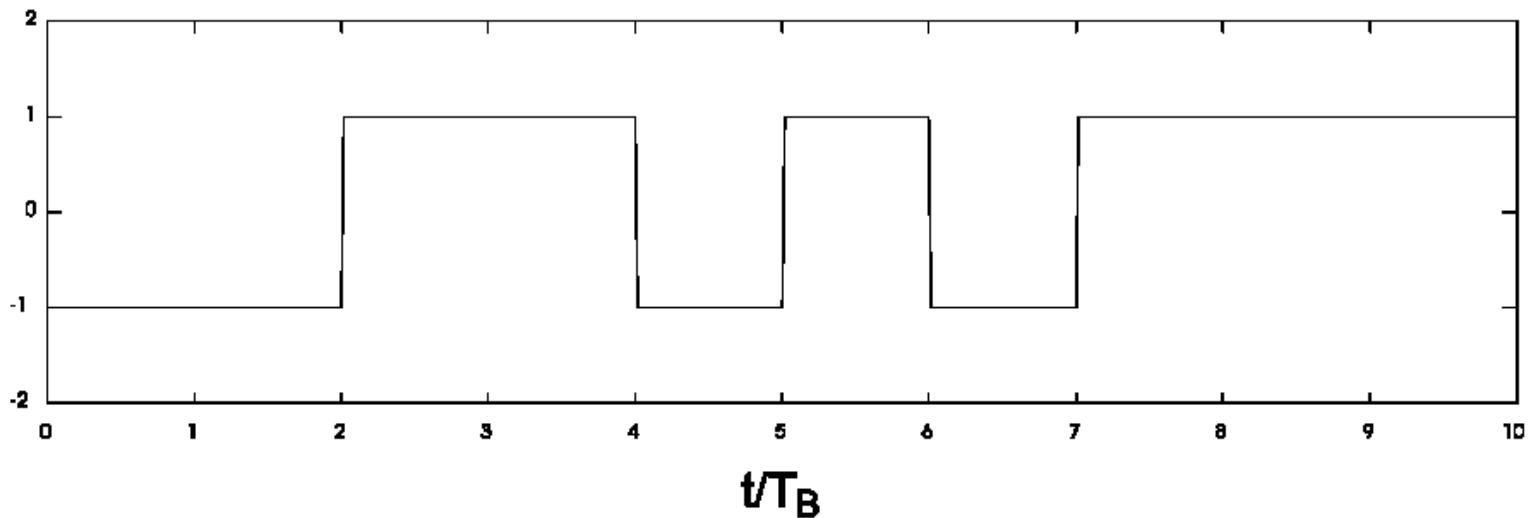
IMPORTANT MODULATION FORMATS



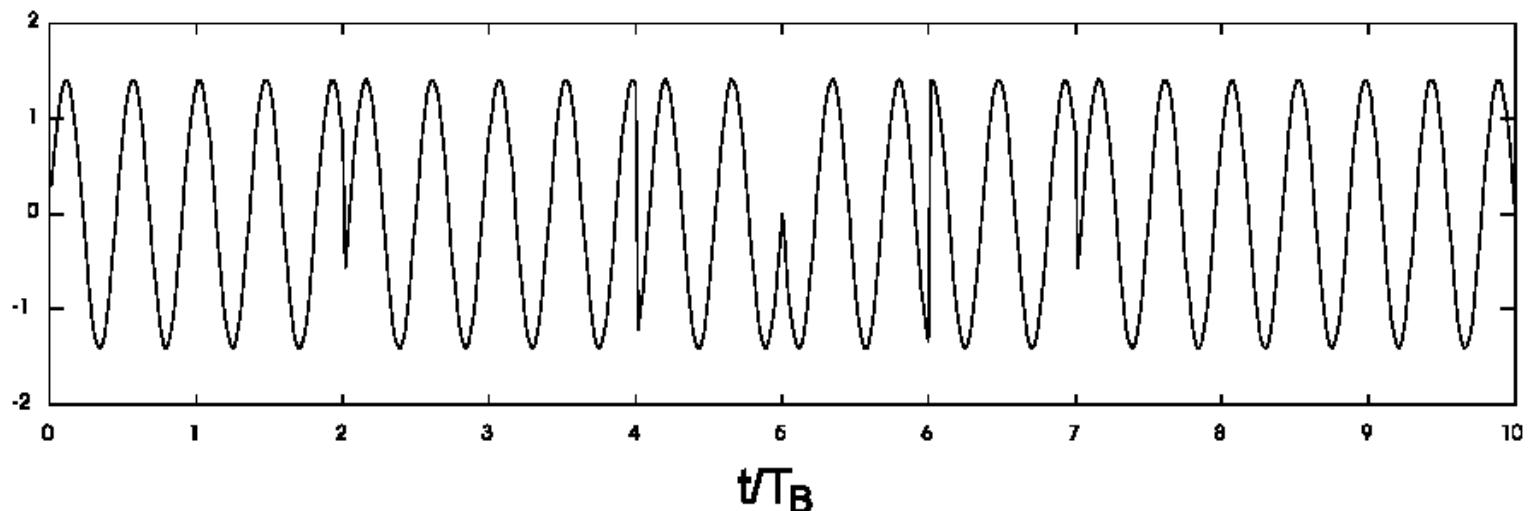
Binary phase-shift keying (BPSK)

Rectangular pulses

Base-band



Radio
signal

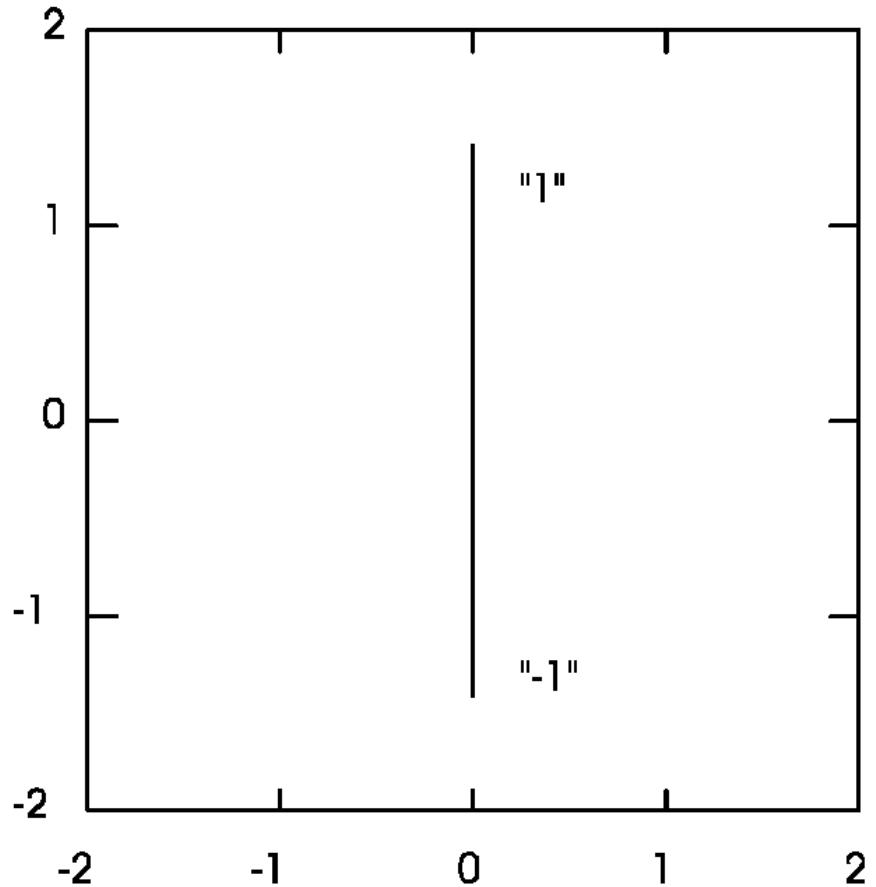




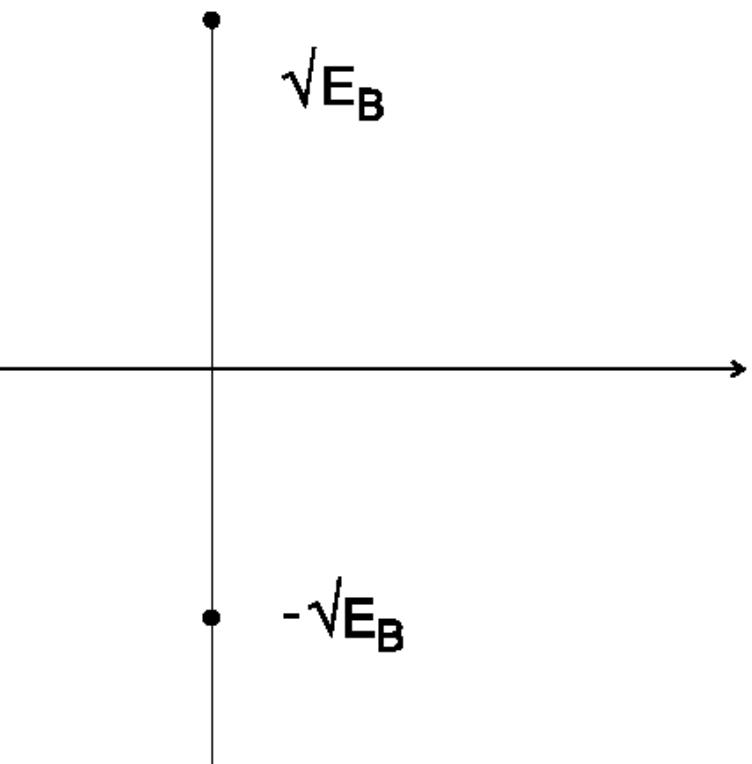
Binary phase-shift keying (BPSK)

Rectangular pulses

Complex representation



Signal constellation diagram

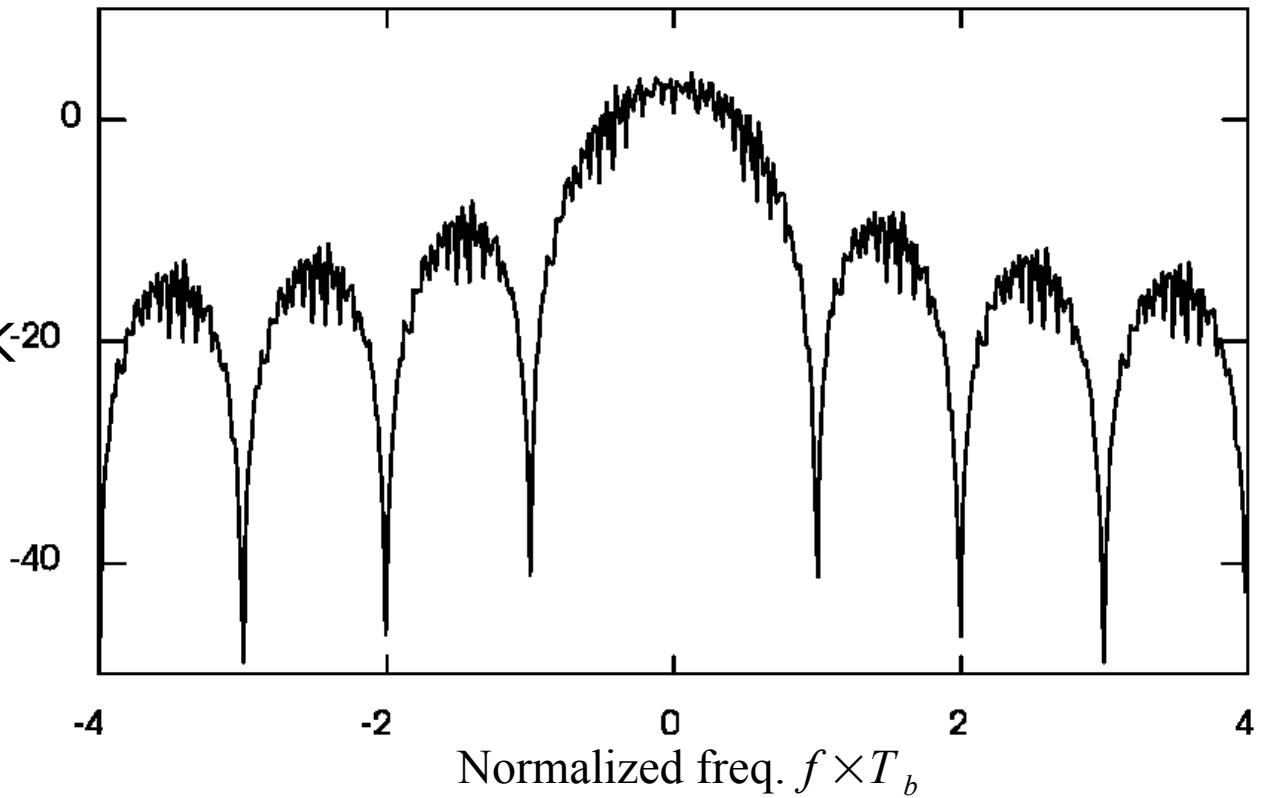




Binary phase-shift keying (BPSK)

Rectangular pulses

Power spectral density for BPSK⁻²⁰

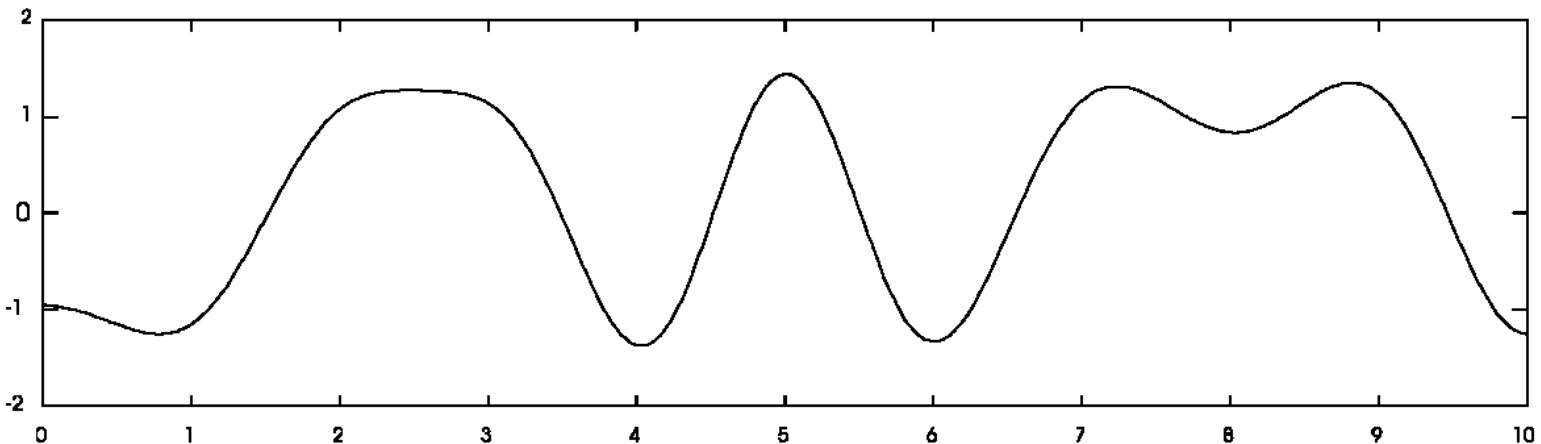


Contained percentage of total energy	spectral efficiency
90%	0.59 Bit/s/Hz
99%	0.05 Bit/s/Hz

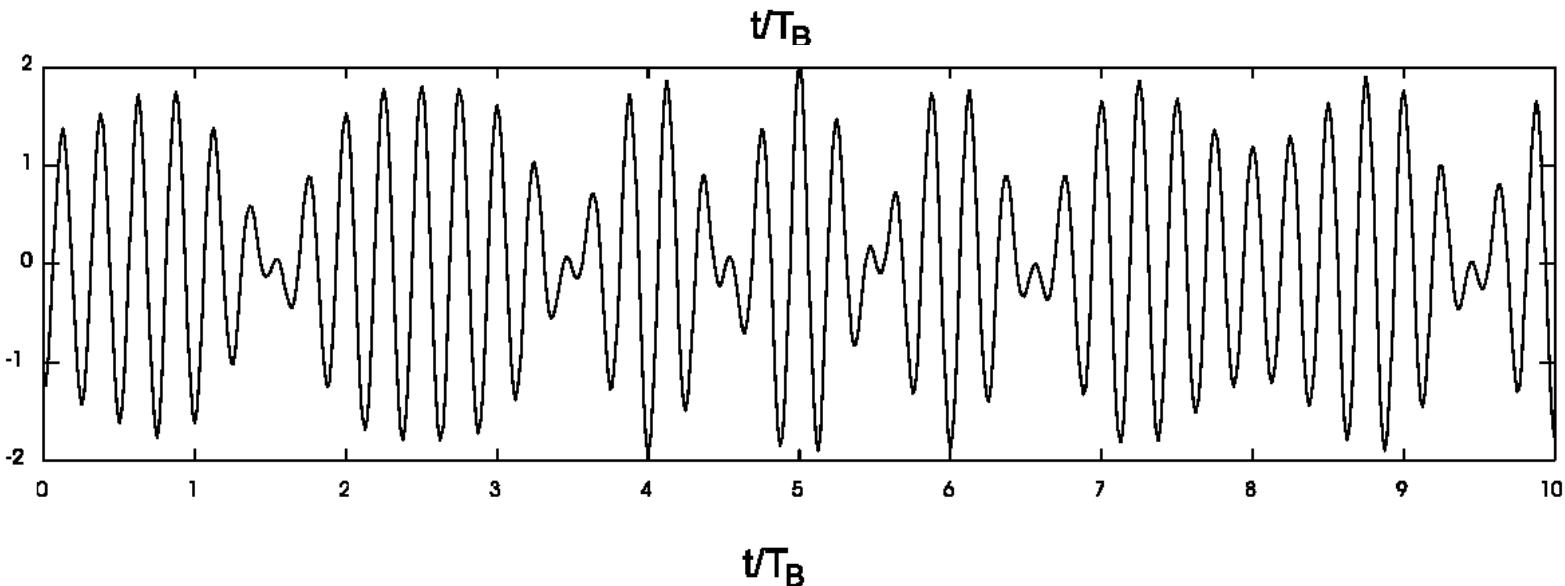


Binary phase-shift keying (BPSK) Raised-cosine pulses (roll-off 0.5)

Base-band



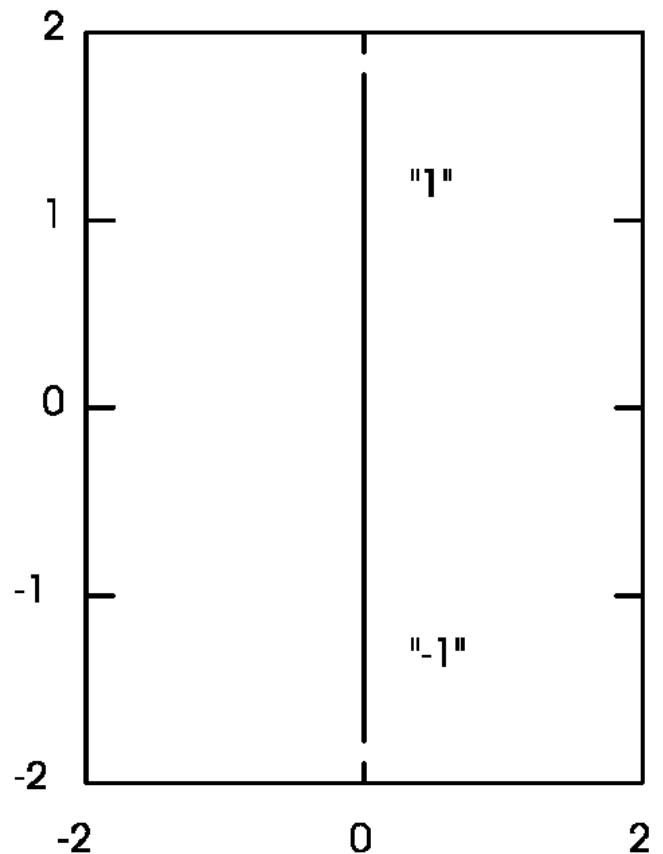
Radio
signal



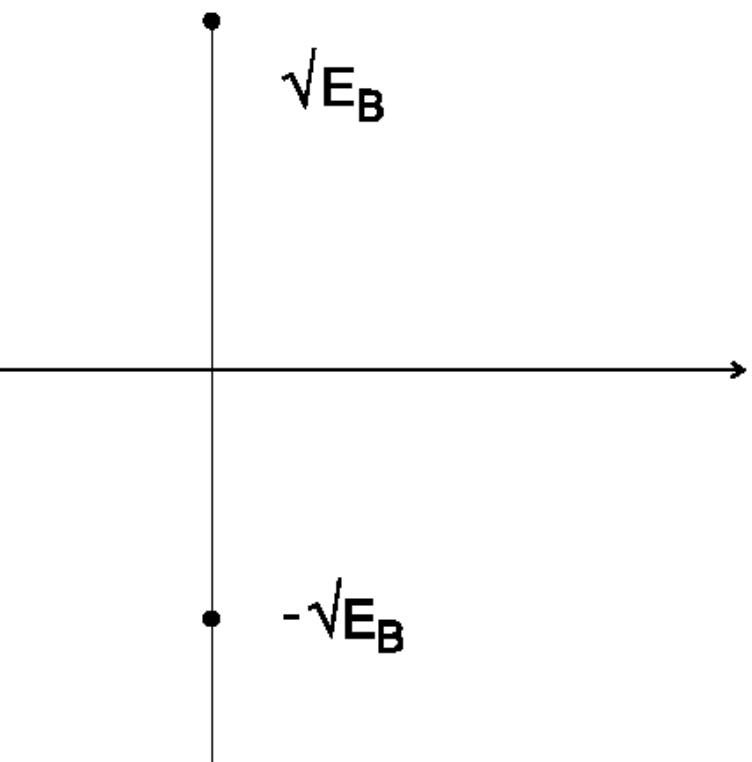
Binary phase-shift keying (BPSK) Raised-cosine pulses (roll-off 0.5)



Complex representation



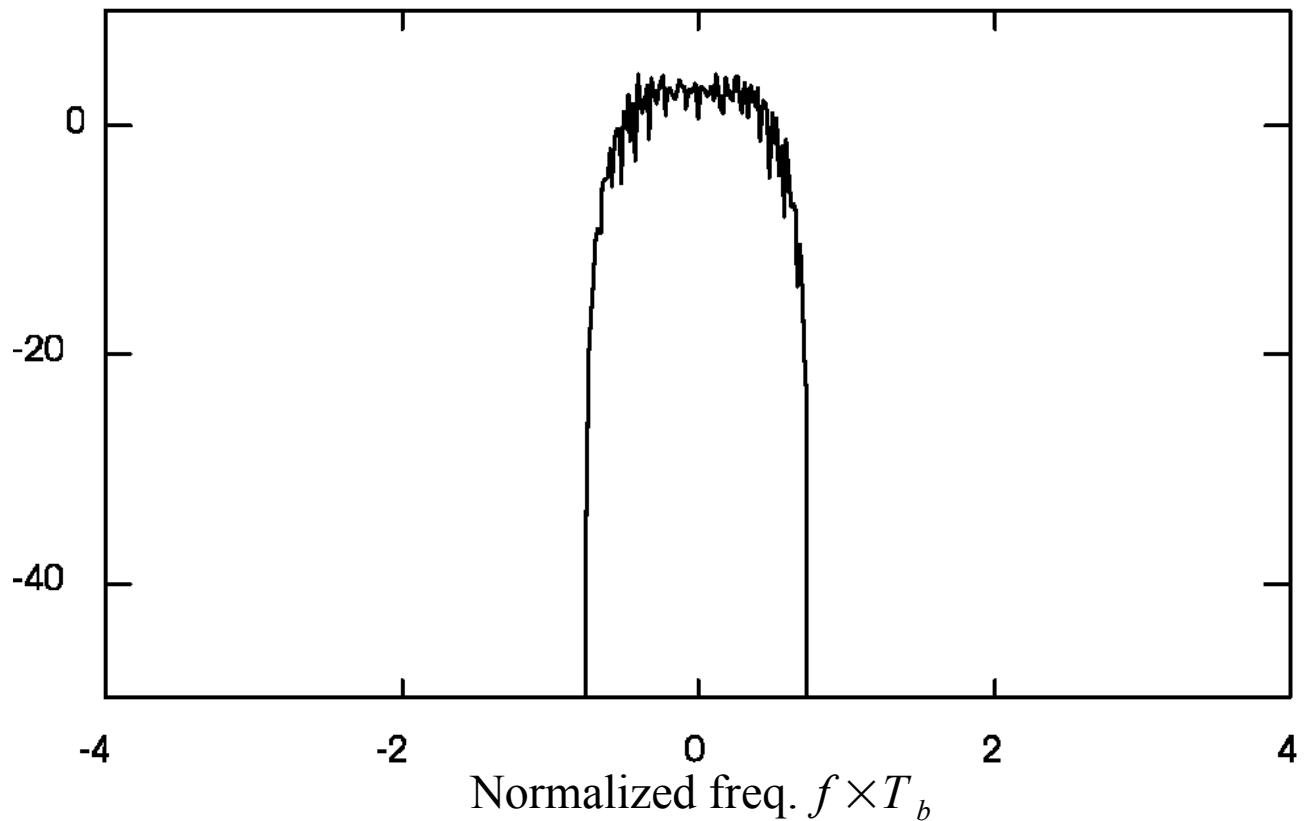
Signal constellation diagram





Binary phase-shift keying (BPSK) Raised-cosine pulses (roll-off 0.5)

Power spectral density for BAM



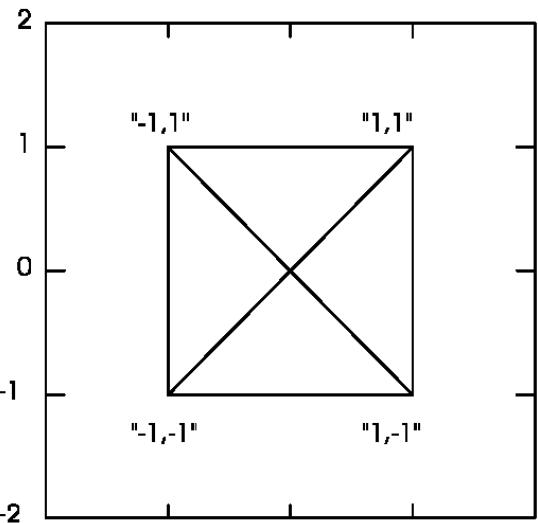
Contained percentage of total energy	spectral efficiency
90%	1.02 Bit/s/Hz
99%	0.79 Bit/s/Hz

Much higher spectral efficiency than BPSK (with rectangular pulses).

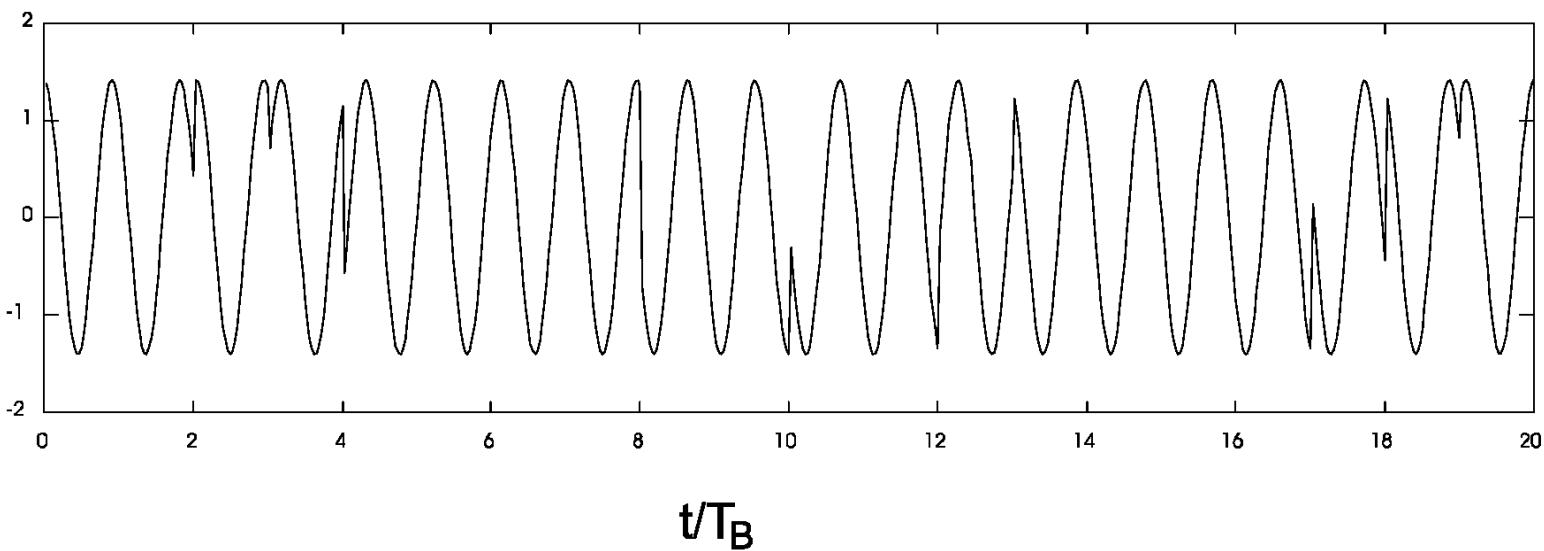
Quaternary PSK (QPSK or 4-PSK) Rectangular pulses



Complex representation

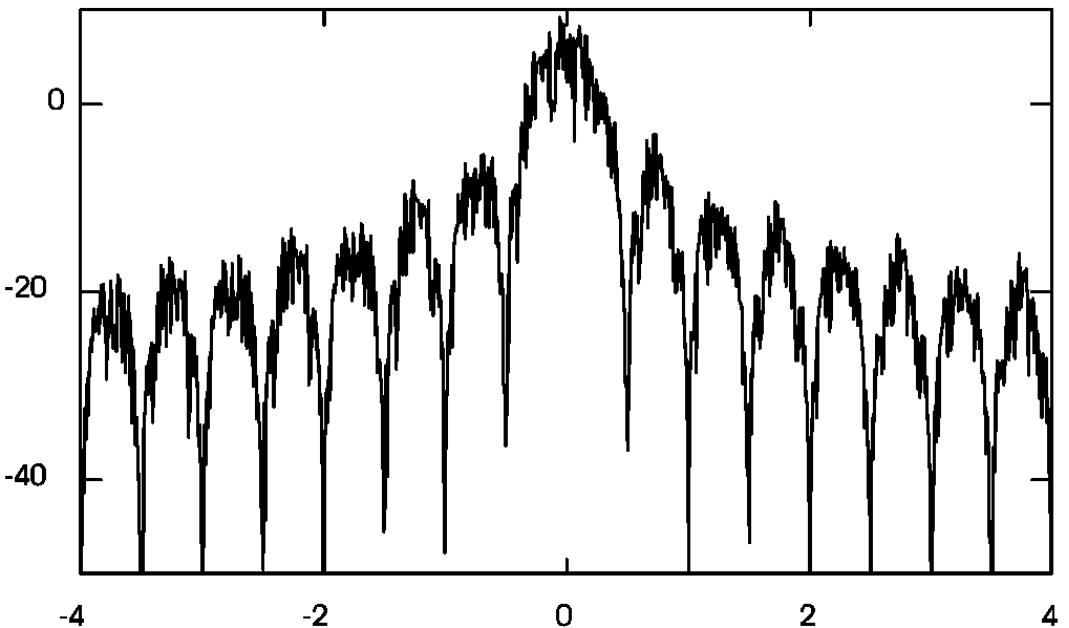


Radio
signal



Quaternary PSK (QPSK or 4-PSK) Rectangular pulses

Power spectral density for QPSK



$$(f-f_c)T_B$$

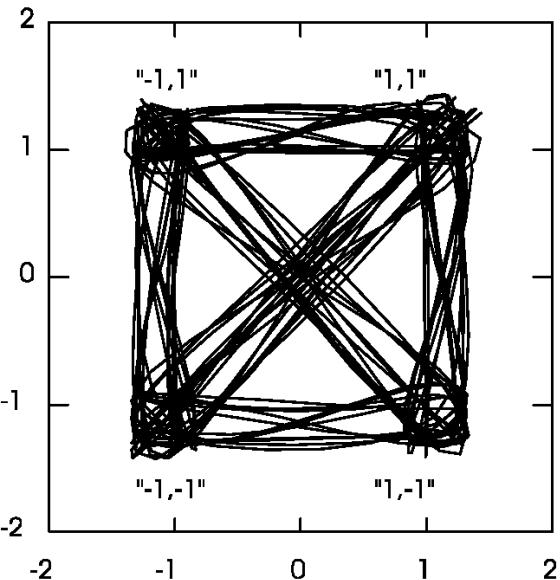
Contained percentage of total energy	spectral efficiency
90%	1.18 Bit/s/Hz
99%	0.10 Bit/s/Hz

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

Quadrature ampl.-modulation (QAM) Root raised-cos pulses (roll-off 0.5)



Complex representation



Contained percentage of total energy	spectral efficiency
90%	2.04 Bit/s/Hz
99%	1.58 Bit/s/Hz

Much higher spectral efficiency than QPSK (with rectangular pulses).

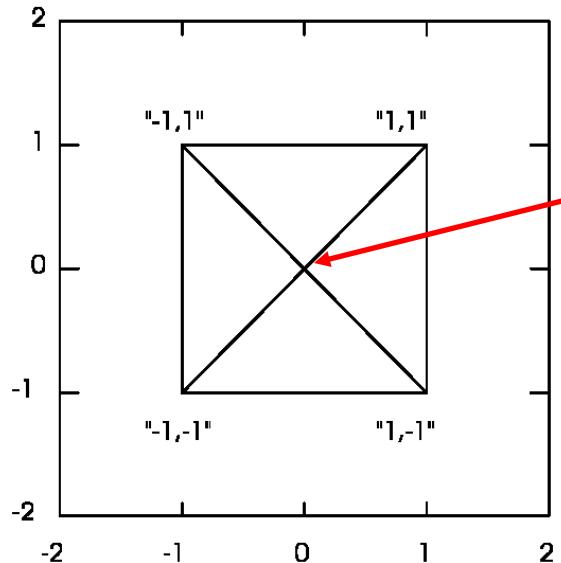
Amplitude variations

The problem



Signals with high amplitude variations leads to less efficient amplifiers.

Complex representation of QPSK



It is a problem that the signal passes through the origin, where the amplitude is ZERO.
(Infinite amplitude variation.)

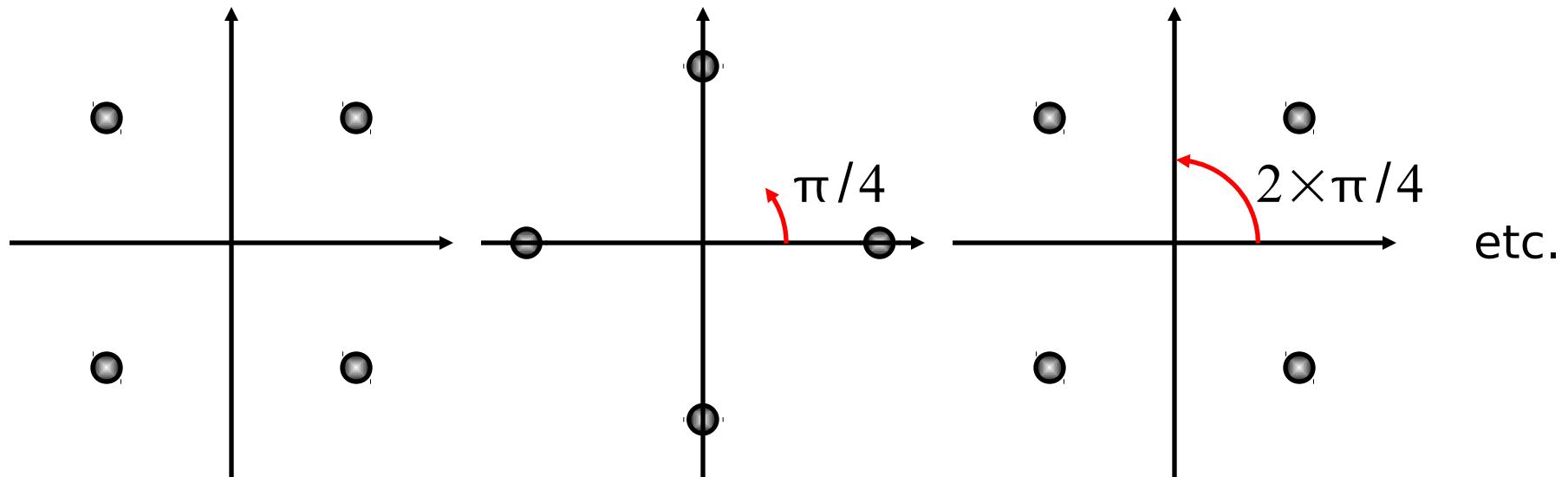
Can we solve this problem in a simple way?

Amplitude variations

A solution



Let's rotate the signal constellation diagram for each transmitted symbol!



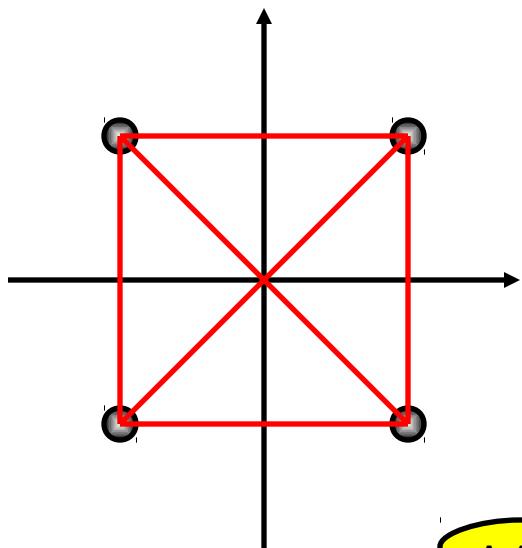
Amplitude variations

A solution

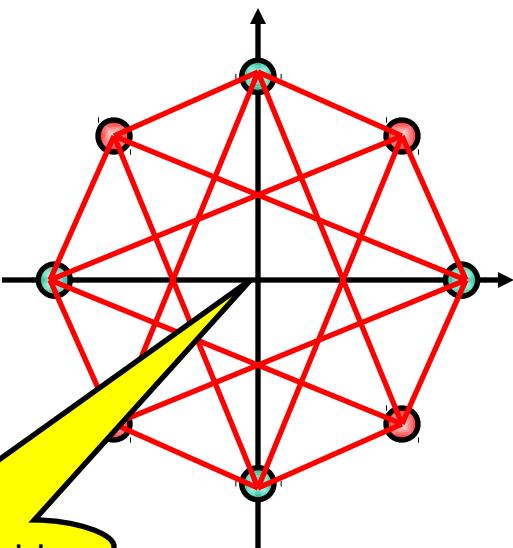


Looking at the complex representation ...

QPSK without rotation



QPSK with rotation

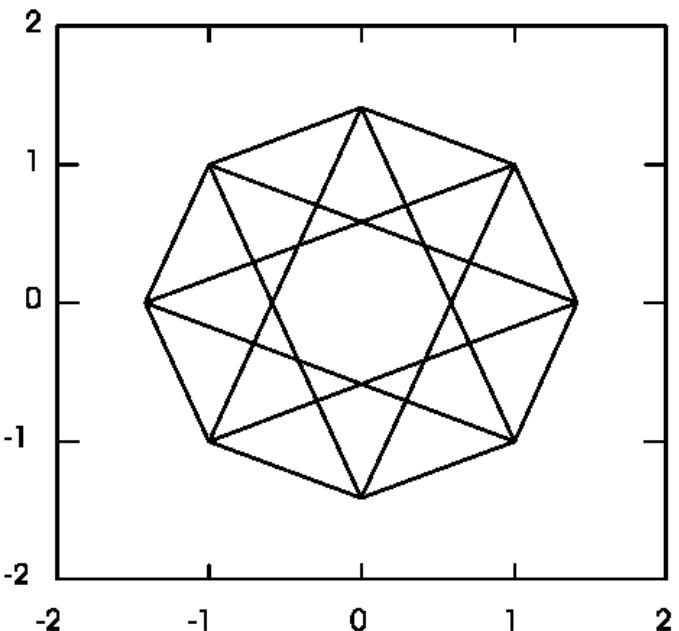


A “hole” is created
in the center. No close
to zero amplitudes.

$\pi / 4$ - Differential QPSK (DQPSK)



Complex representation

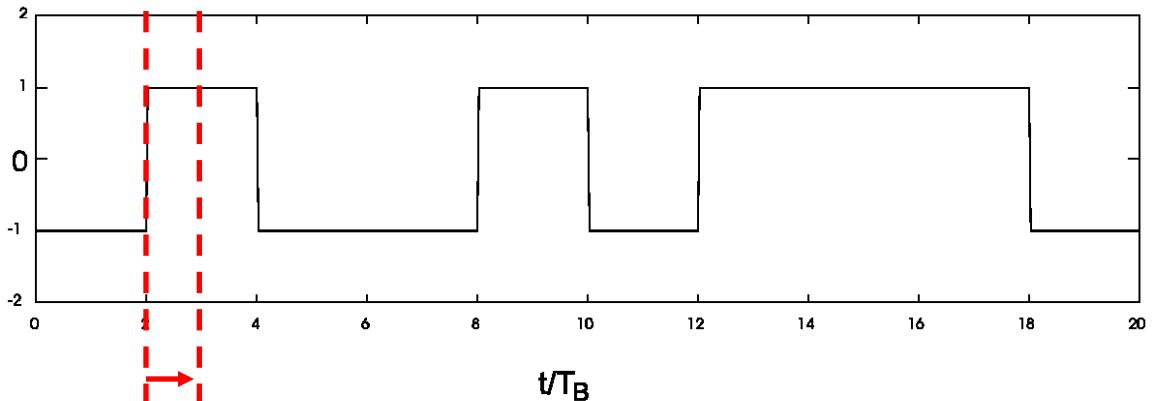


Still uses the same rectangular pulses as QPSK - the power spectral density and the spectral efficiency are the same.

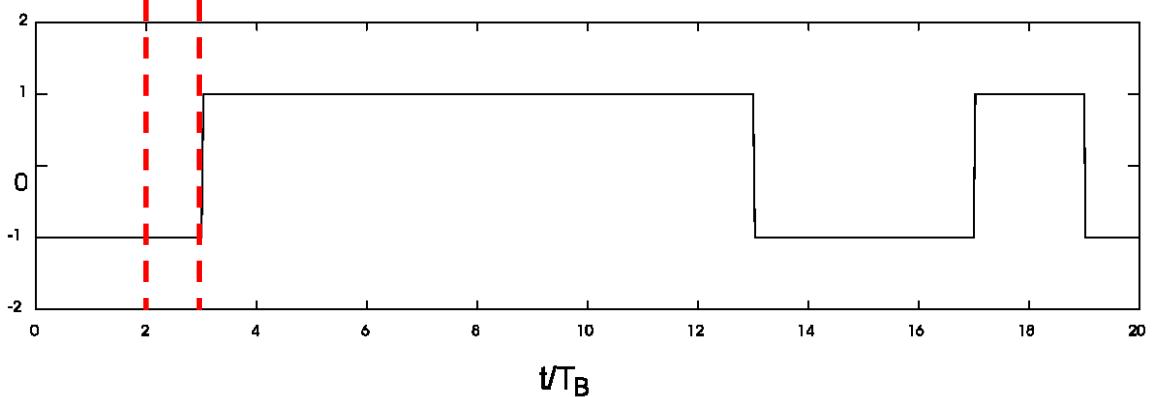
This modulation type is used in several standards for mobile communications (due to its low amplitude variations).

Offset QPSK (OQPSK) Rectangular pulses

In-phase
signal



Quadrature
signal

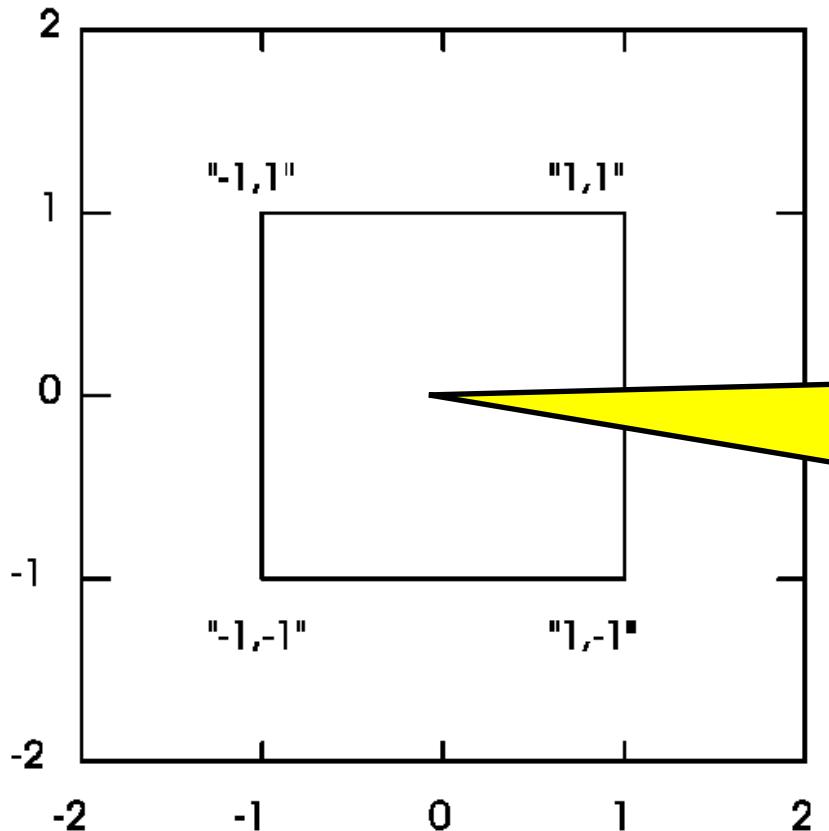


There is **one bit-time** offset between the in-phase and the quadrature part of the signal (a delay on the Q channel). This makes the transitions between pulses take place at different times!

Offset QPSK Rectangular pulses

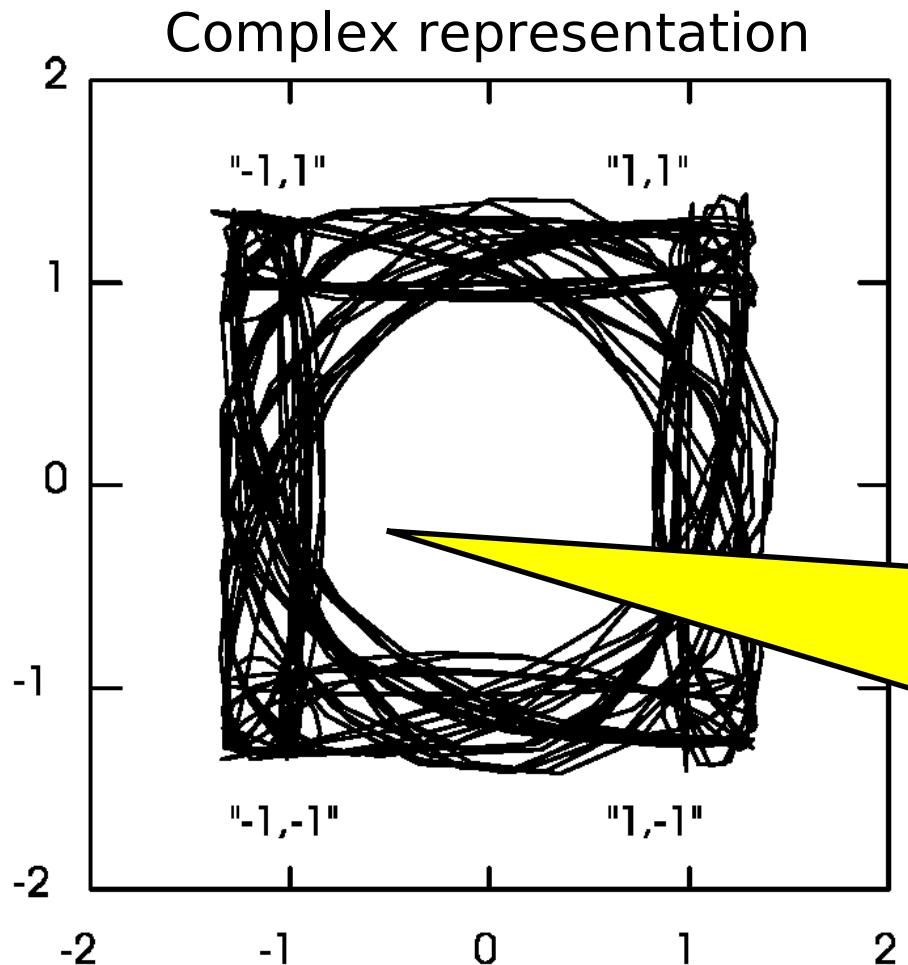


Complex representation



This method also creates a hole in the center, giving less amplitude variations.

Offset QAM (OQAM) Raised-cosine pulses



This method also creates a hole in the center, but has larger amplitude variations than OQPSK.

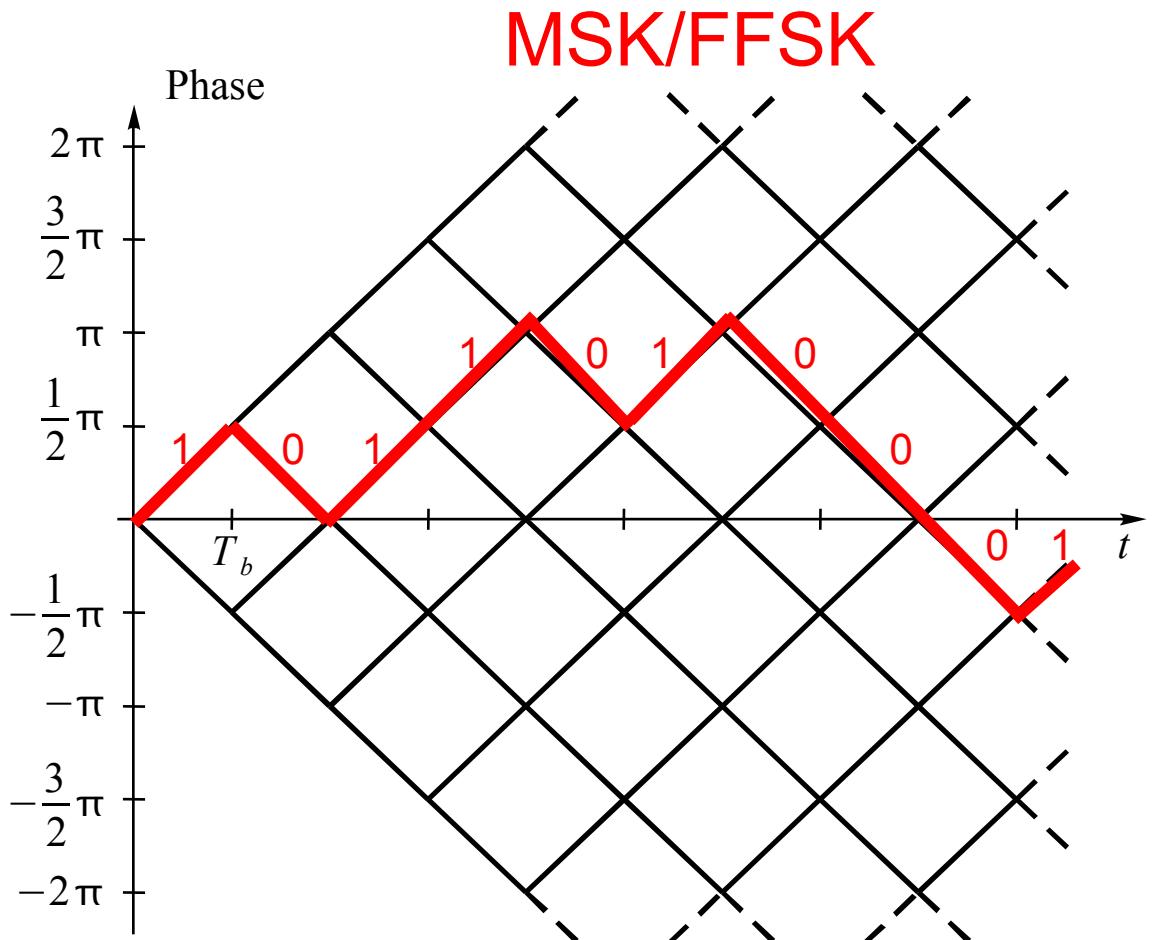
Continuous-phase modulation

Basic idea:

- Keep amplitude constant
- Change phase continuously

In this particular example we change the phase in a piecewise linear fashion by $\pm \pi/2$, depending on the data transmitted.

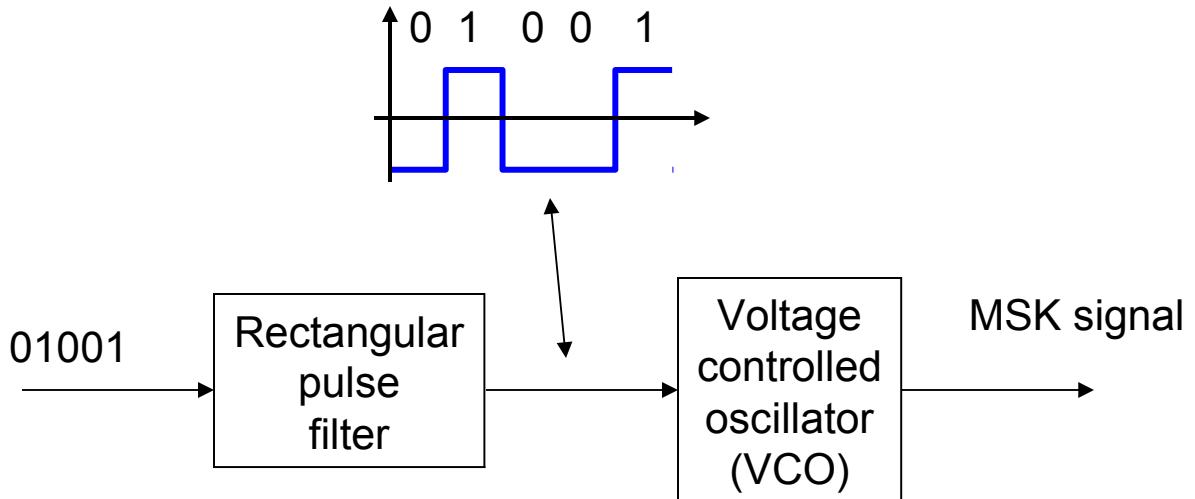
This type of modulation can be interpreted both as phase and frequency modulation. It is called **MSK** (minimum shift keying) or **FFSK** (fast frequency shift keying).





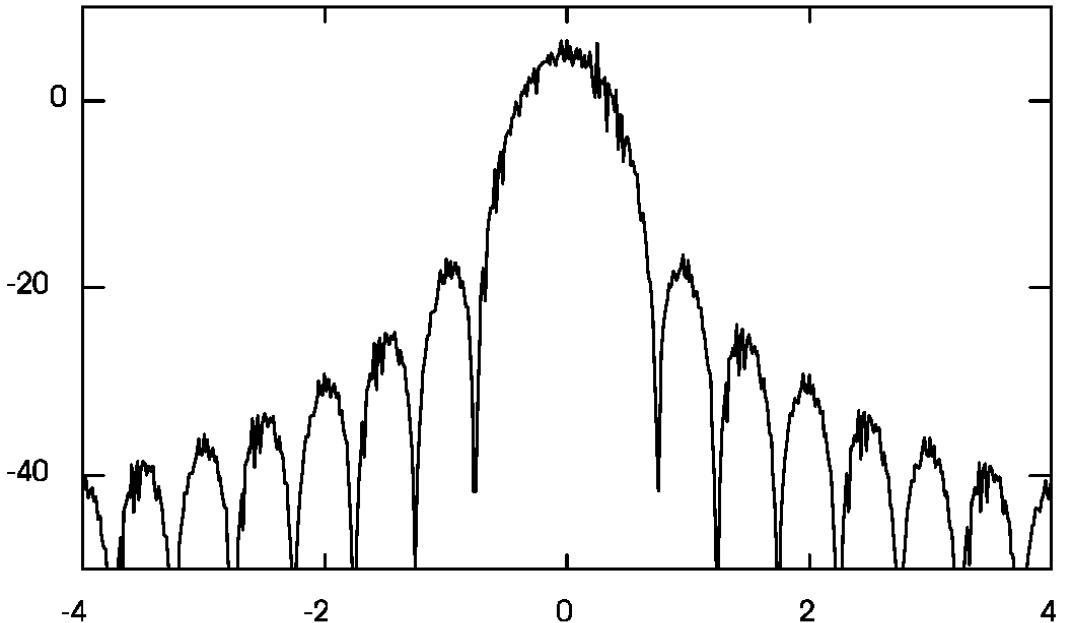
Minimum shift keying (MSK)

Simple MSK implementation



Minimum shift keying (MSK)

Power spectral density of MSK



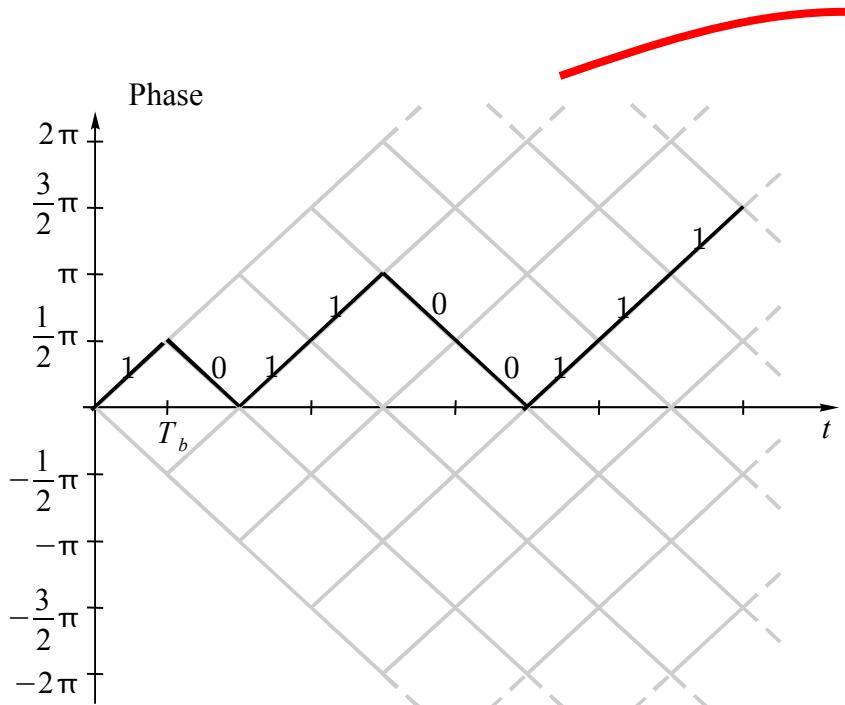
$$(f-f_c)T_B$$

Contained percentage of total energy	spectral efficiency
90 %	1,29 Bit / s / Hz
99 %	0,85 Bit / s / Hz

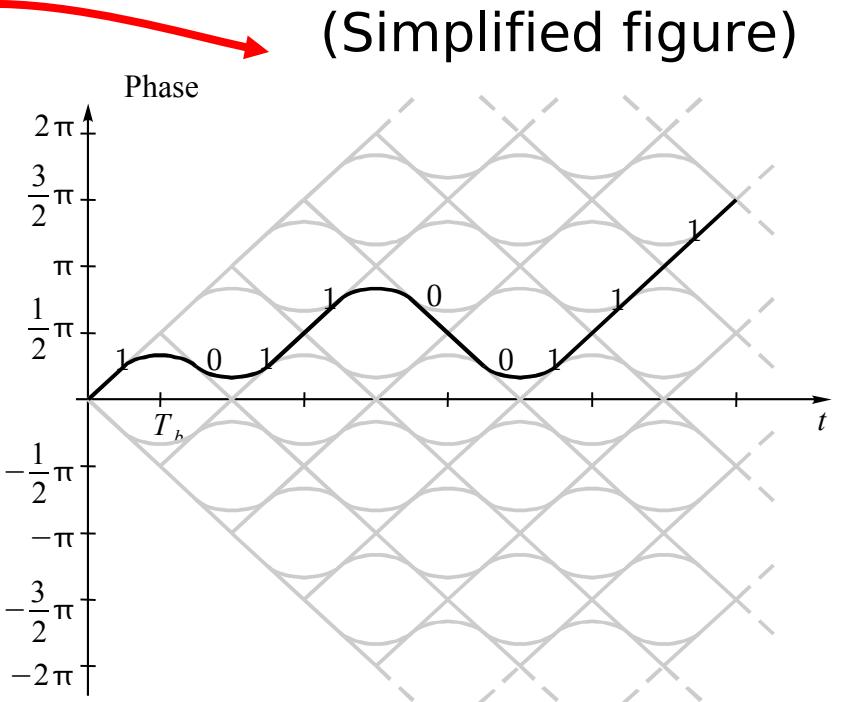
Gaussian filtered MSK (GMSK)



Further improvement of the phase: Remove 'corners'



MSK
(Rectangular pulse filter)

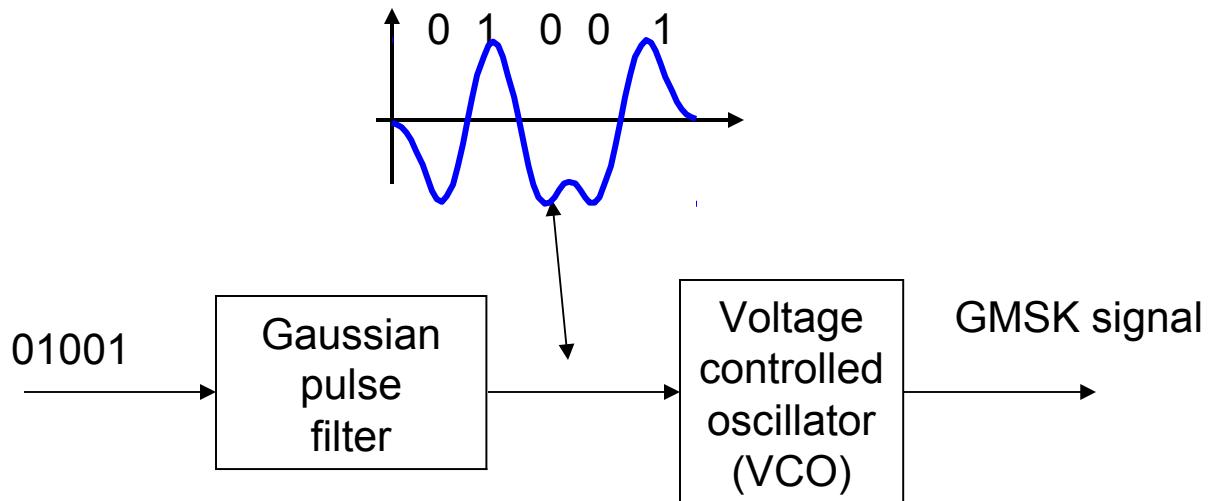


Gaussian filtered MSK - GMSK
(Gaussian pulse filter)



Gaussian filtered MSK (GMSK)

Simple GMSK implementation

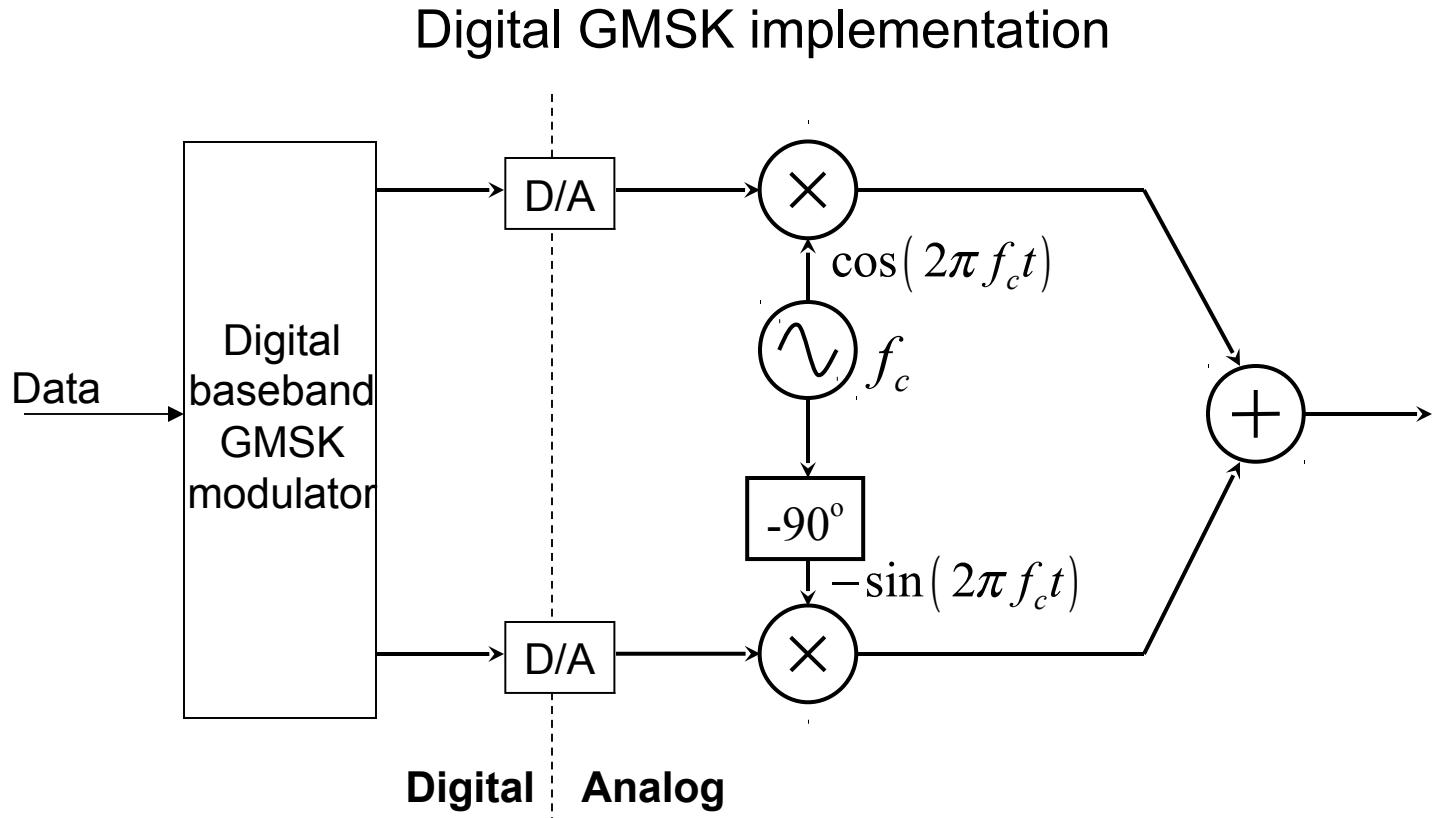


When implemented this “simple” way, it is usually called Gaussian filtered frequency shift keying (GFSK).

GFSK is used in e.g. Bluetooth.



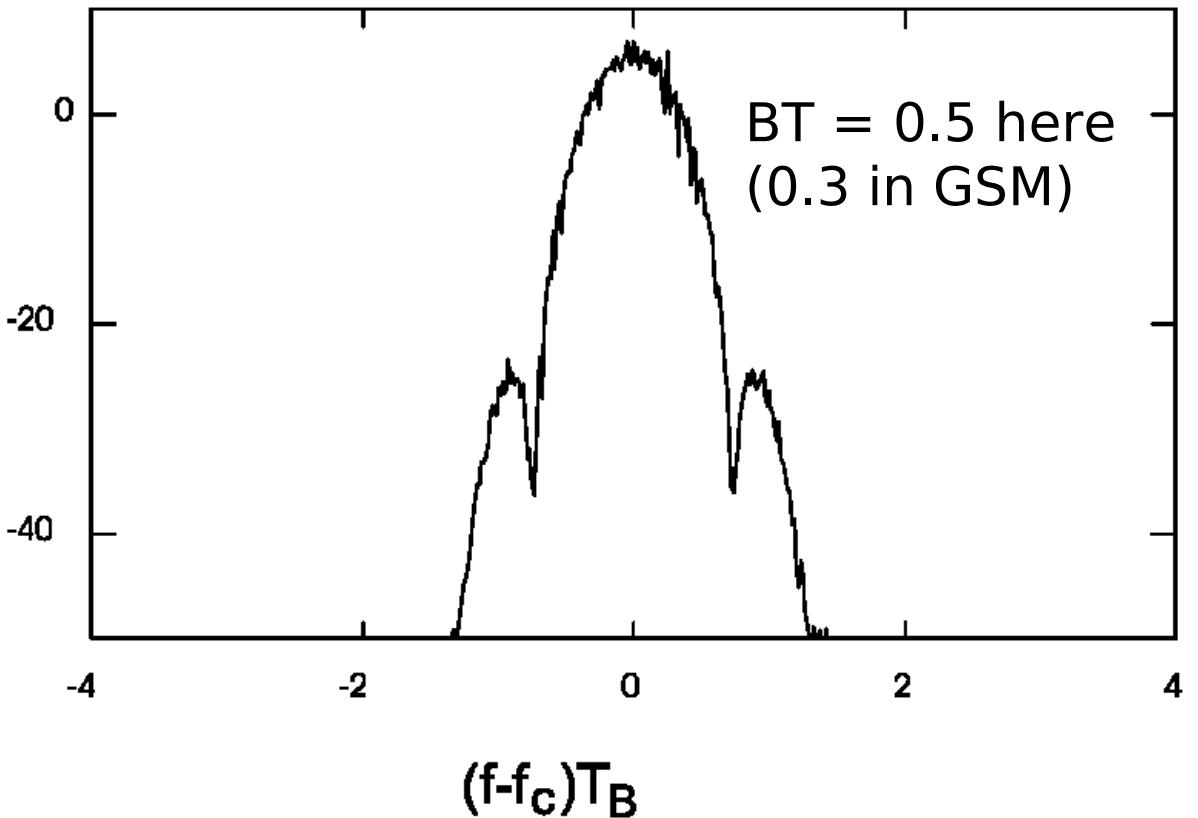
Gaussian filtered MSK (GMSK)



This is a more precise implementation of GMSK, which is used in e.g. GSM.

Gaussian filtered MSK (GMSK)

Power spectral density of GMSK.



Contained percentage of total energy	spectral efficiency
90 %	1,45 Bit / s / Hz
99 %	0,97 Bit / s / Hz



How do we use all these spectral efficiencies?

Example: Assume that we want to use MSK to transmit 50 kbit/sec, and want to know the required transmission bandwidth.

Take a look at the spectral efficiency table:

Contained percentage of total energy	spectral efficiency
90 %	1,29 Bit / s / Hz
99 %	0,85 Bit / s / Hz

The 90% and 99% bandwidths become:

$$B_{90\%} = 50000 / 1.29 = 38.8 \text{ kHz}$$

$$B_{99\%} = 50000 / 0.85 = 58.8 \text{ kHz}$$



Summary

BPSK with
root-raised
cosine
pulses

Modulation method	spectral efficiency	spectral efficiency
	for 90 % of total energy	for 99 % of total energy
	Bit / s / Hz	Bit / s / Hz
BPSK	0,59	0,05
BAM ($\alpha=0.5$)	1,02	0,79
QPSK, OQPSK,	1,18	0,10
MSK	1,29	0,85
GMSK ($B_G T = 0.5$)	1,45	0,97
QAM ($\alpha = 0.5$)	2,04	1,58

TABLE 11.1 in textbook.