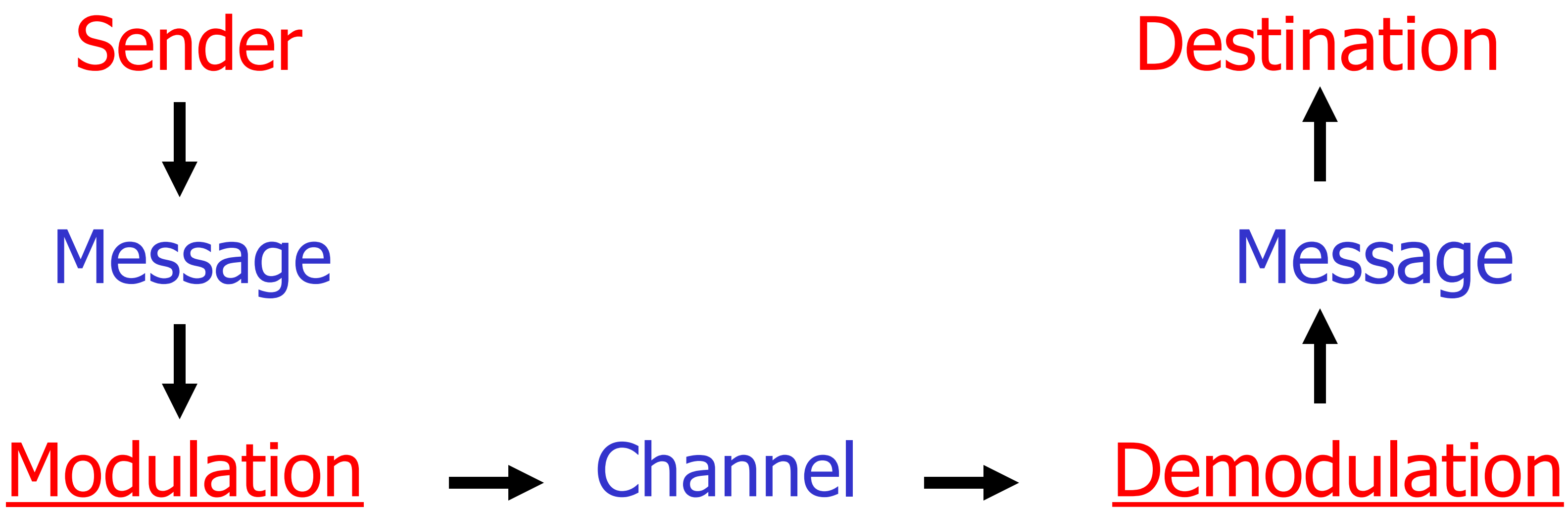
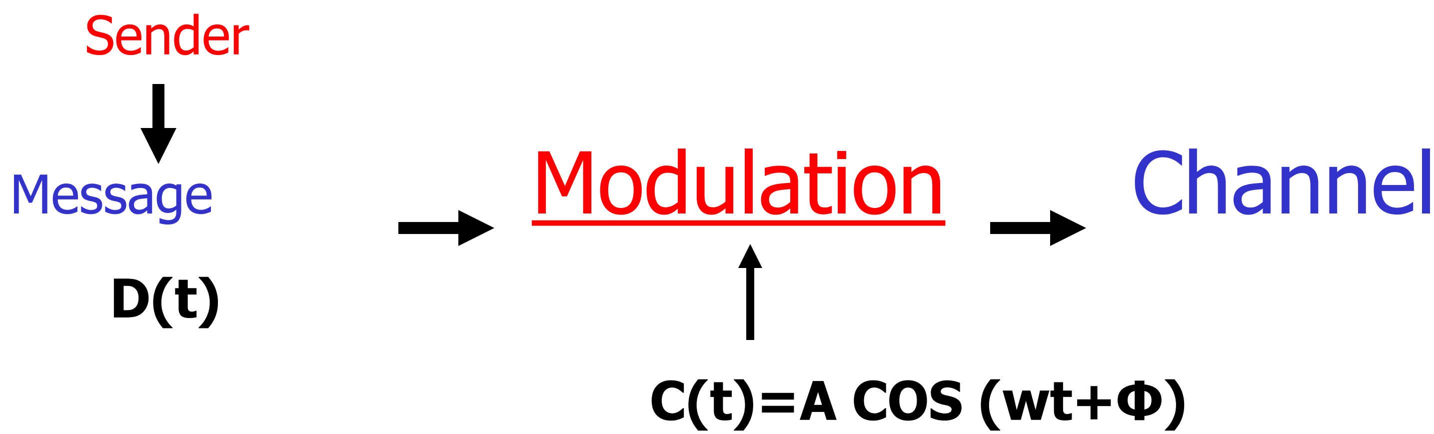
Digital Modulation Techniques in Mobile Communications

Digital Modulation Technique



Modulation Techniques

- Modulation is the process of encoding information from a message source in a manner suitable for transmition.
- The ultimate goal of a modulation technique is to transport the message signal through a radio channel with the best possible quality while occupying the least amount of radio spectrum.



- Modulation may be done by varying the amplitude ,phase, or frequency of a high frequency carrier in accordance with the amplitude of the message signal.

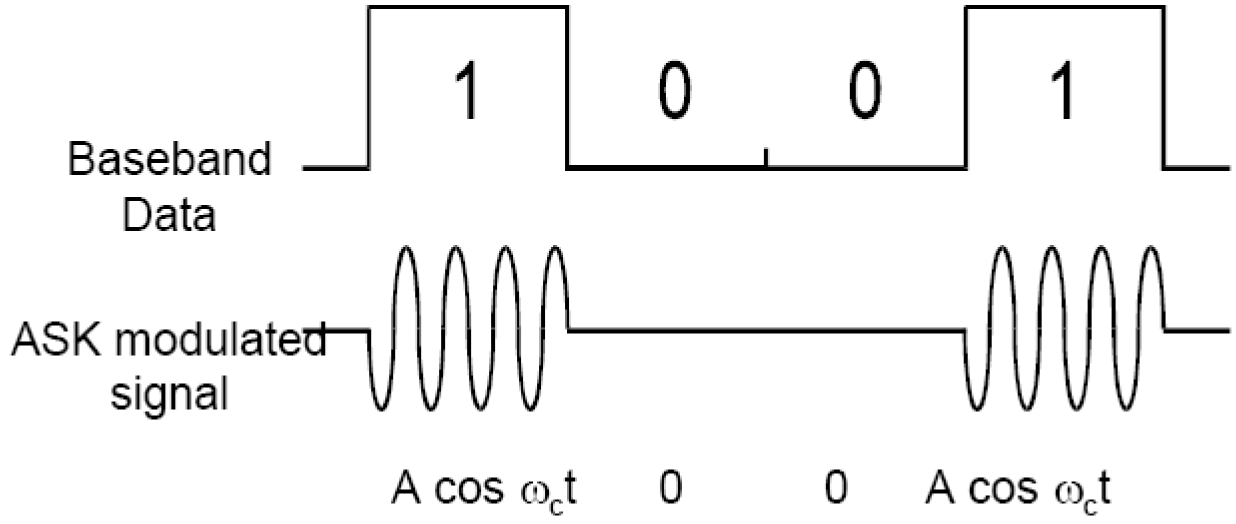
$$C(t) = A \cos(wt + \Phi)$$

A → **ASK**

w → **FSK**

Φ → **PSK**

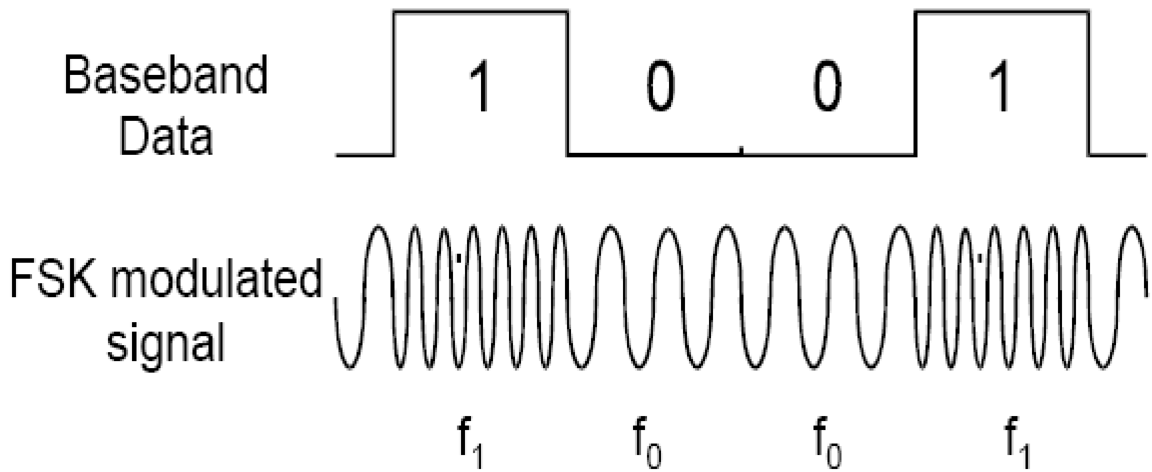
Amplitude Shift Keying (ASK)



- Pulse shaping can be employed to remove spectral spreading.

- ASK demonstrates poor performance, as it is heavily affected by noise and interference.

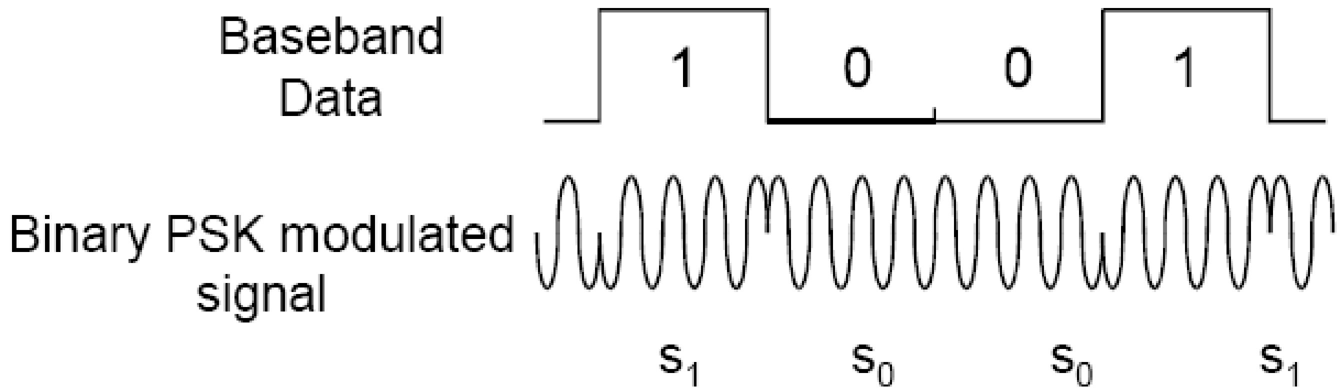
Frequency Shift Keying (FSK)



where $f_0 = A\cos(\omega_c - \Delta\omega)t$ and $f_1 = A\cos(\omega_c + \Delta\omega)t$

- Bandwidth occupancy of FSK is dependant on the spacing of the two symbols. A frequency spacing of 0.5 times the symbol period is typically used.
- FSK can be expanded to a M-ary scheme, employing multiple frequencies as different states.

Phase Shift Keying (PSK)



where $s_0 = -A \cos \omega_c t$ and $s_1 = A \cos \omega_c t$

- Binary Phase Shift Keying (BPSK) demonstrates better performance than ASK and FSK.

- PSK can be expanded to a M-ary scheme, employing multiple phases and amplitudes as different states.

- Filtering can be employed to avoid spectral spreading.

PSK & DPSK

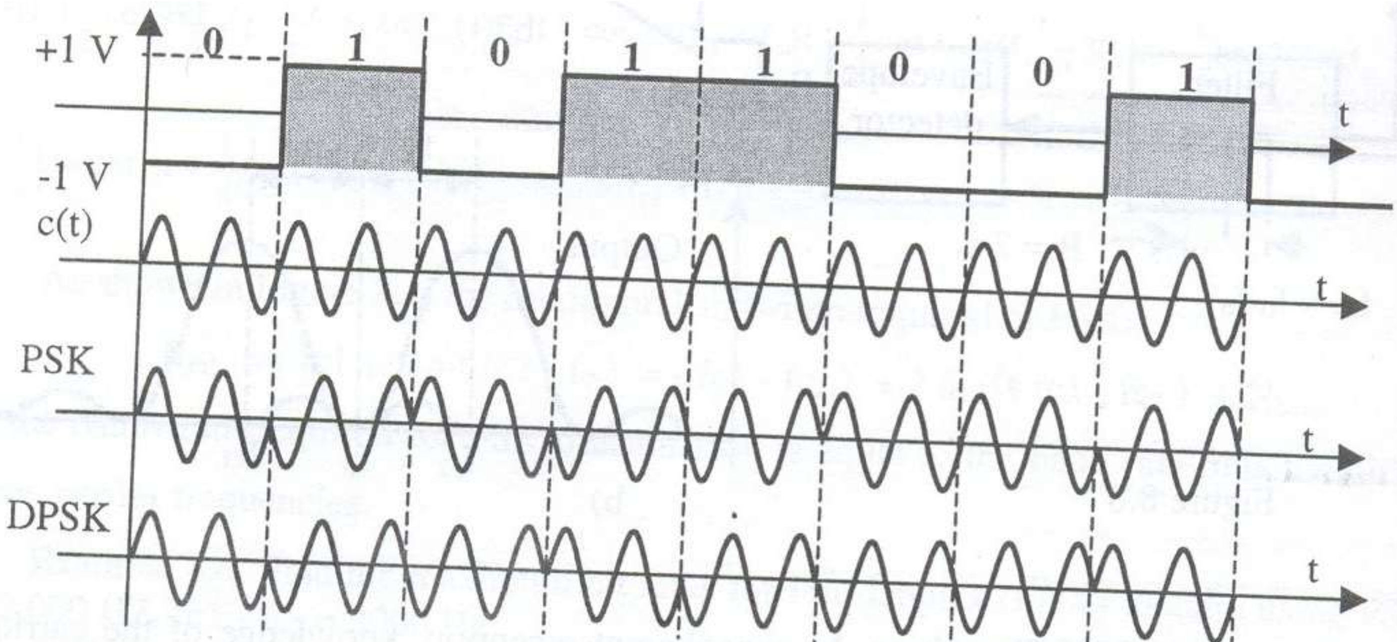


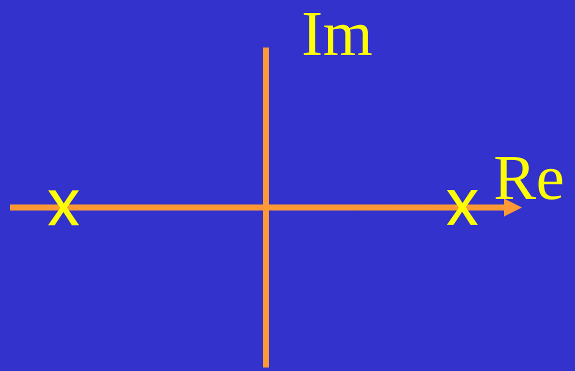
Figure 8.9

Multi-Phase

Binary Phase Shift Keying (BPSK)

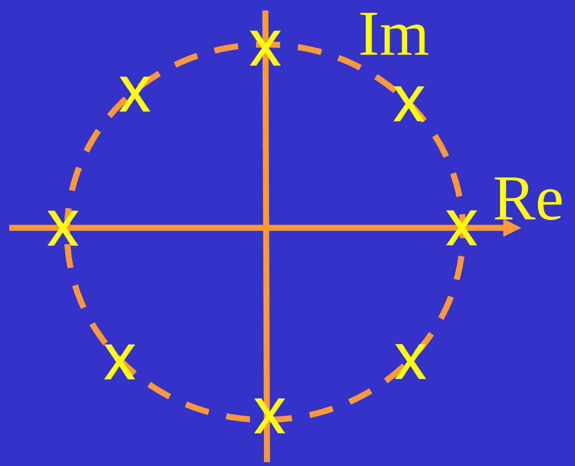
1: $\phi_1(t) = p(t)\cos(\omega_c t)$

0: $\phi_0(t) = p(t)\cos(\omega_c t + \pi)$

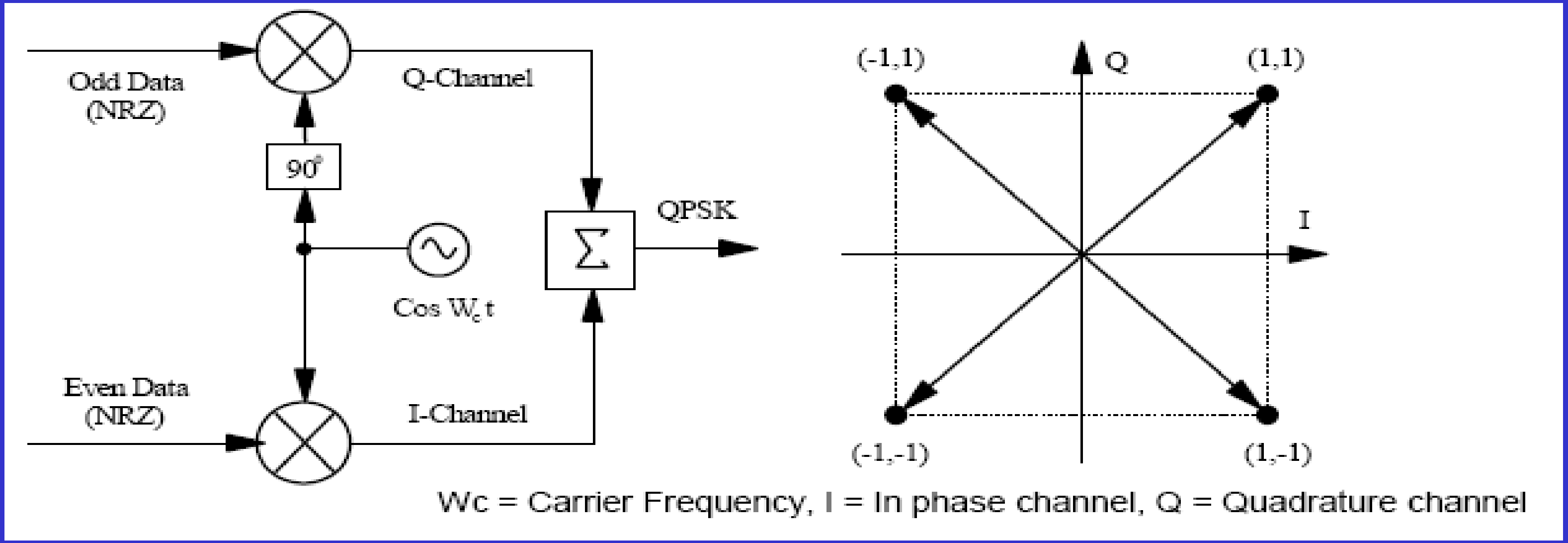


M-ary PSK

$$p_k(t) = p(t)\cos\left(\omega_c t + \frac{2\pi}{M}k\right)$$

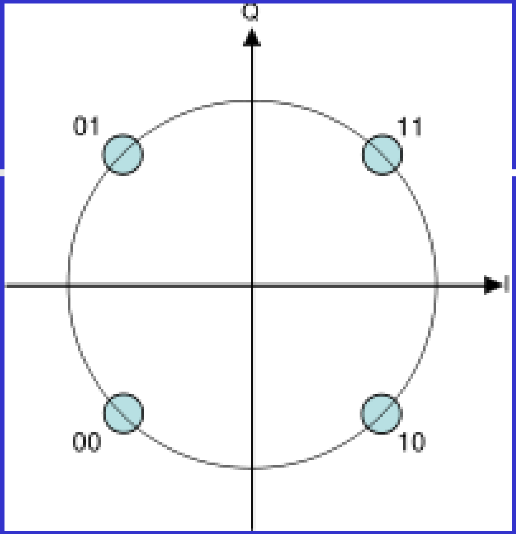


QPSK



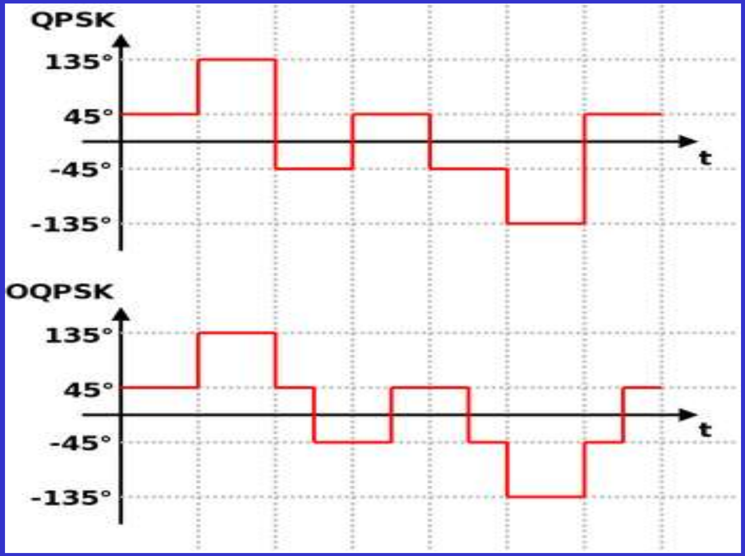
*** Quadrature Phase Shift Keying is effectively two independent BPSK systems (I and Q), and therefore exhibits the same performance but *twice* the bandwidth efficiency.**
*** Quadrature Phase Shift Keying can be filtered using raised cosine filters to achieve excellent out of band suppression.**
*** Large envelope variations occur during phase transitions, thus requiring *linear* amplification.**

Quadrature Phase-Shift Keying (QPSK)



Constellation diagram for QPSK with Gray coding. Each adjacent symbol only differs by one bit.

QPSK can encode two bits per symbol, shown in the diagram with Gray coding to minimize the BER twice the rate of BPSK.



QPSK may be used either to double the data rate compared to a BPSK system while maintaining the bandwidth of the signal or to maintain the data-rate of BPSK but halve the bandwidth needed.

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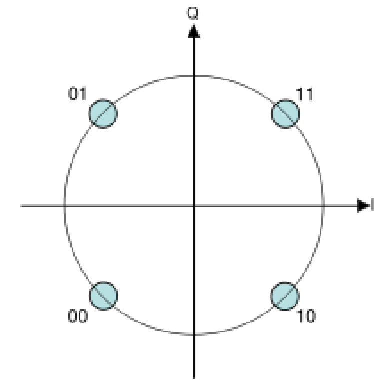
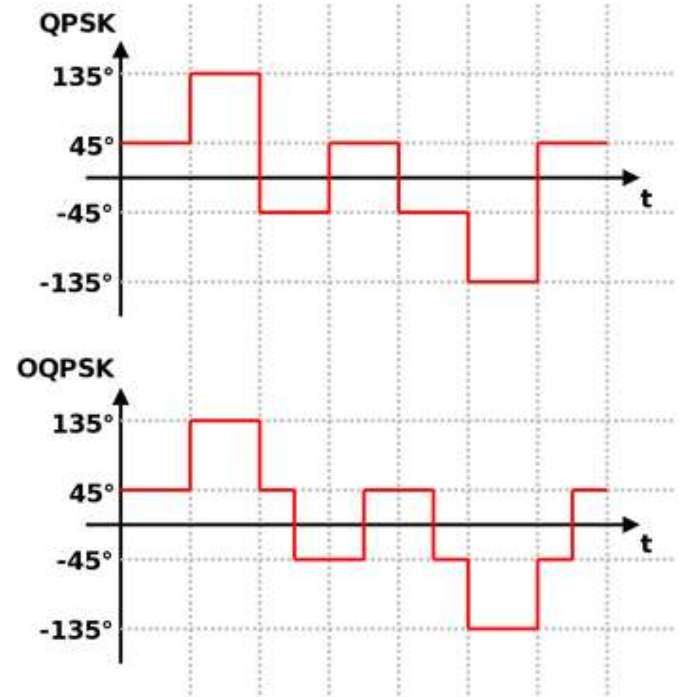
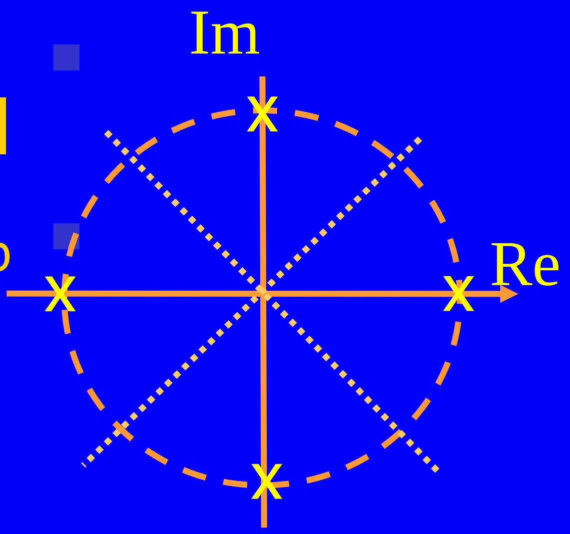
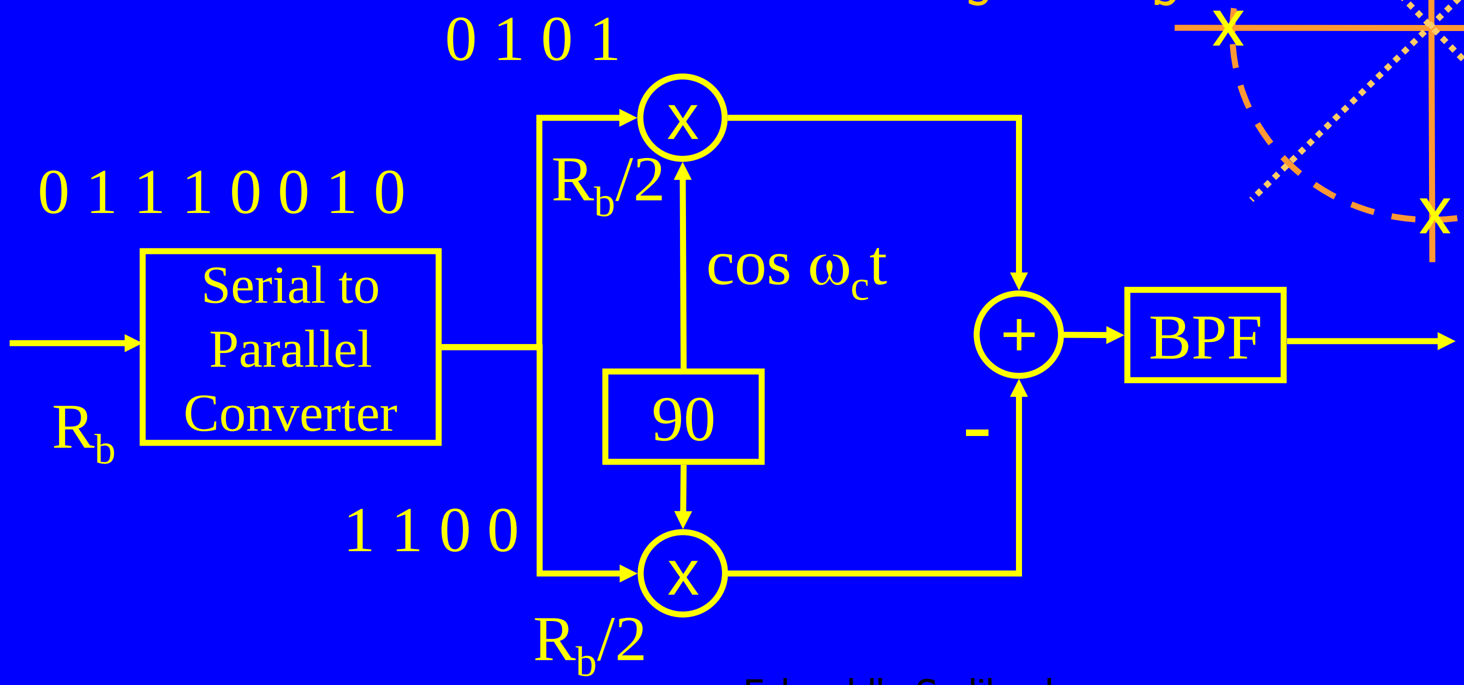


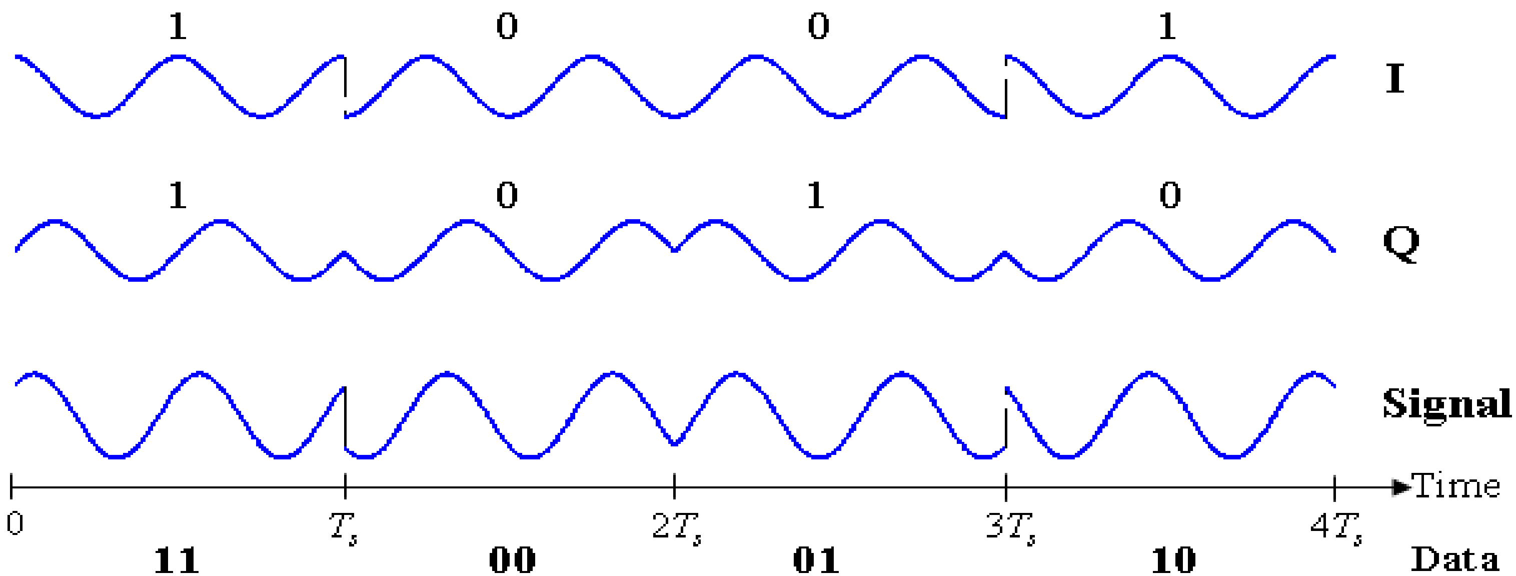


QPSK

- Modeled as two BPSK systems in parallel
- $T_s = 2\,T_b$

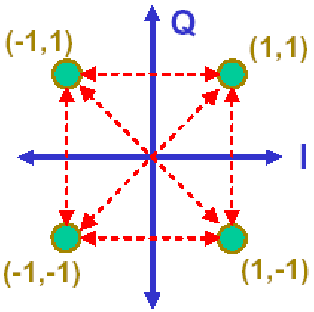




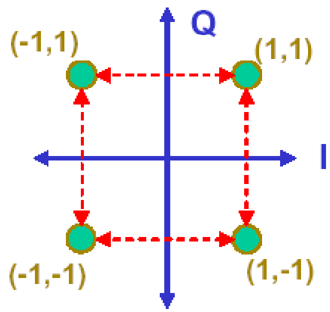


- The binary data that is conveyed by this waveform is: 1 1 0 0 0 1 1 0.
- The odd bits, highlighted here, contribute to the in-phase component: **1** 1 **0** 0 **0** 1 **1** 0. The even bits, highlighted here, contribute to the quadrature-phase component: 1 **1** 0 **0** 0 **1** 1 **0** .
- In the timing diagram for QPSK. The binary data stream is shown beneath the time axis. The two signal components with their bit assignments are shown the top and the total, combined signal at the bottom. Note the abrupt changes in phase at some of the bit-period boundaries which are not satisfied.

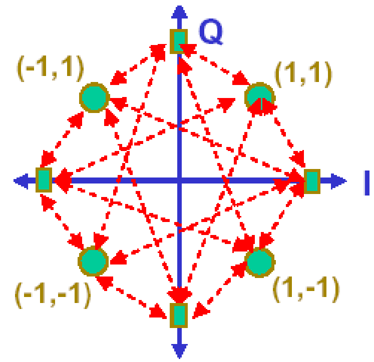
QPSK TYPES



Conventional QPSK



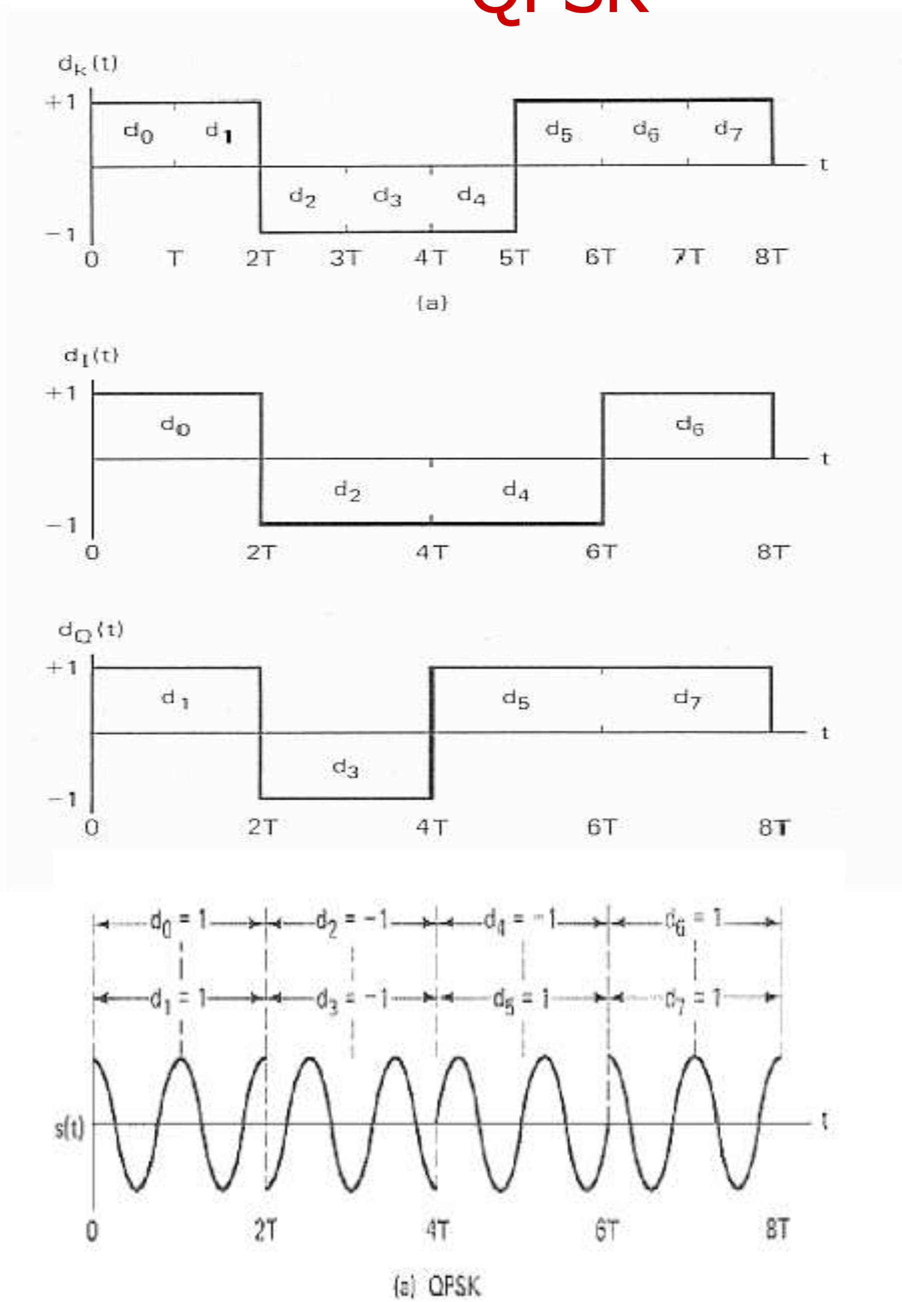
Offset QPSK



π/4 QPSK

- **Conventional QPSK** has transitions through zero (ie. 180° phase transitions). A highly linear amplifier is required.
- In **Offset QPSK**, the transitions on the I and Q channels are staggered. Phase transitions are therefore limited to 90°.
- In **π/4-QPSK** the set of constellation points are toggled for each symbol, so transitions through zero cannot occur. This scheme produces the lowest envelope variations.
- All QPSK schemes require linear power amplifiers.

QPSK



dk(t)
+1
−1
d0
d1
d2
d3
d4
d5
d6
d7
t
0
T
2T
3T
4T
5T
6T
7T
8T
(a)
dI(t)
dQ(t)
s(t)
d0 = 1
d2 = −1
d4 = −1
d6 = 1
d1 = 1
d3 = −1
d5 = 1
d7 = 1
(a) QPSK

A convenient orthogonal realisation of a QPSK waveform , s(t) is achieved by amplitude modulating the in-phase and quadrature data streams onto the cosine and sine functions of a carrier wave as follows:

$$s(t)=1/\sqrt{2}\, d_I(t) \cos(2\pi ft + \pi/4) + 1/\sqrt{2}\, d_Q(t) \sin(2\pi ft + \pi/4)$$

Using trigonometric identities this can also be written as

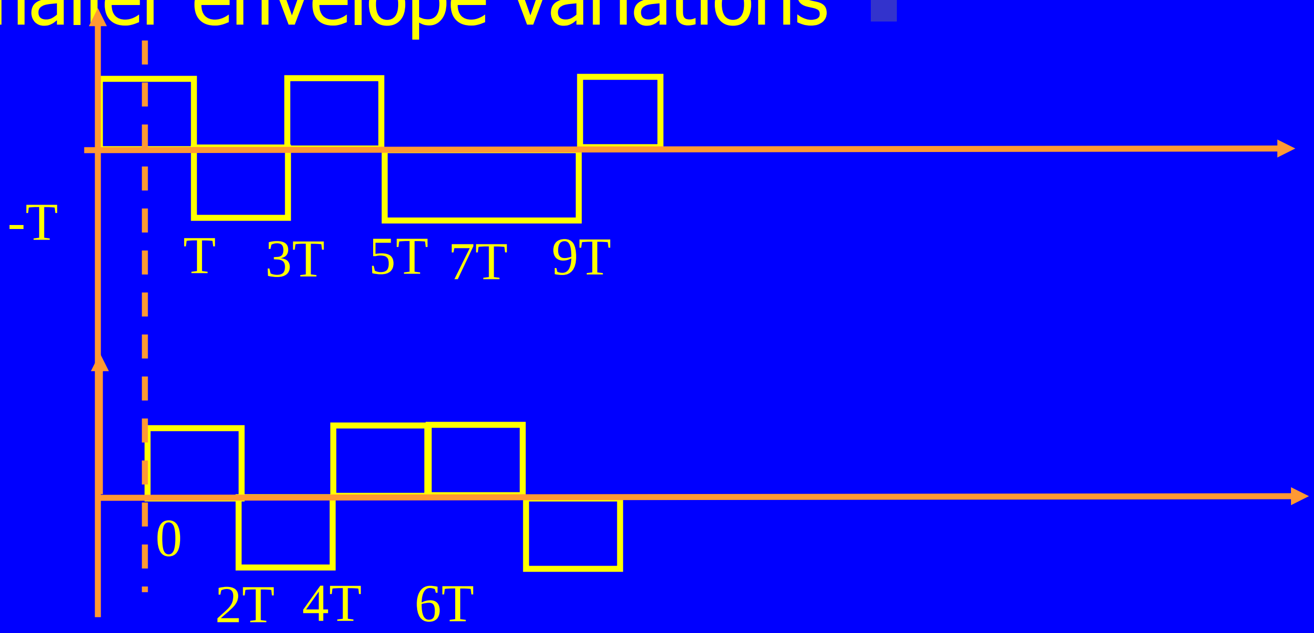
$$s(t)=A \cos[2\pi ft + \pi/4 + \theta(t)].$$

Offset QPSK (OQPSK)

- Ideally amplitude of QPSK signal is constant
- If pulses are shaped, then constant envelope is lost and phase shift of π radians causes waveform to go to zero briefly
- Can only use less efficient linear amplifiers
- OQPSK or Staggered QPSK
- Waveforms are shifted by ½ bit

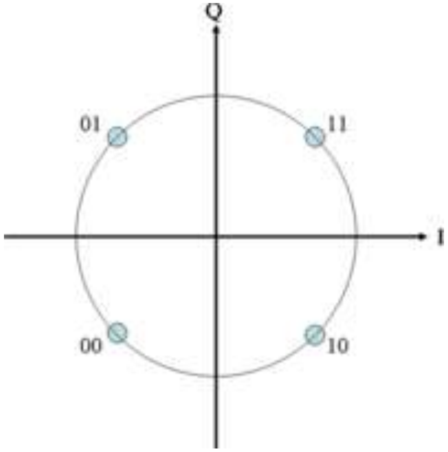
OQPSK

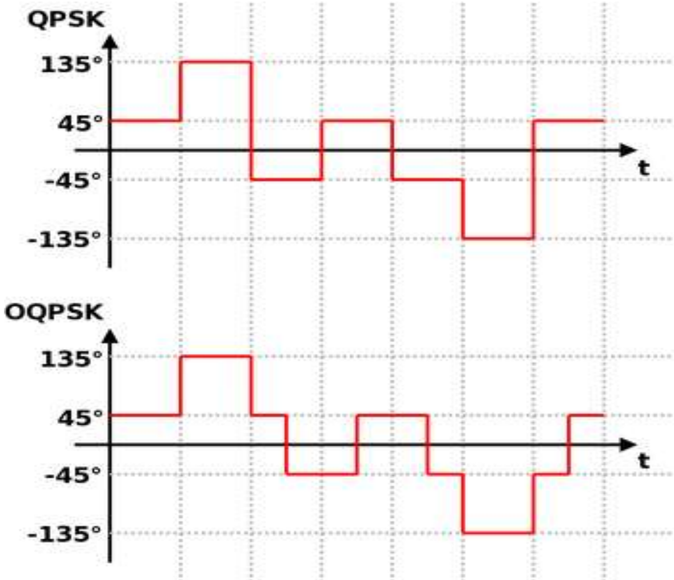
- Bit transitions occur every T_b sec
- Limited to changes of +/- $\pi/2$
- Smaller envelope variations



Offset Quadrature Phase-Shift Keying (OQPSK)

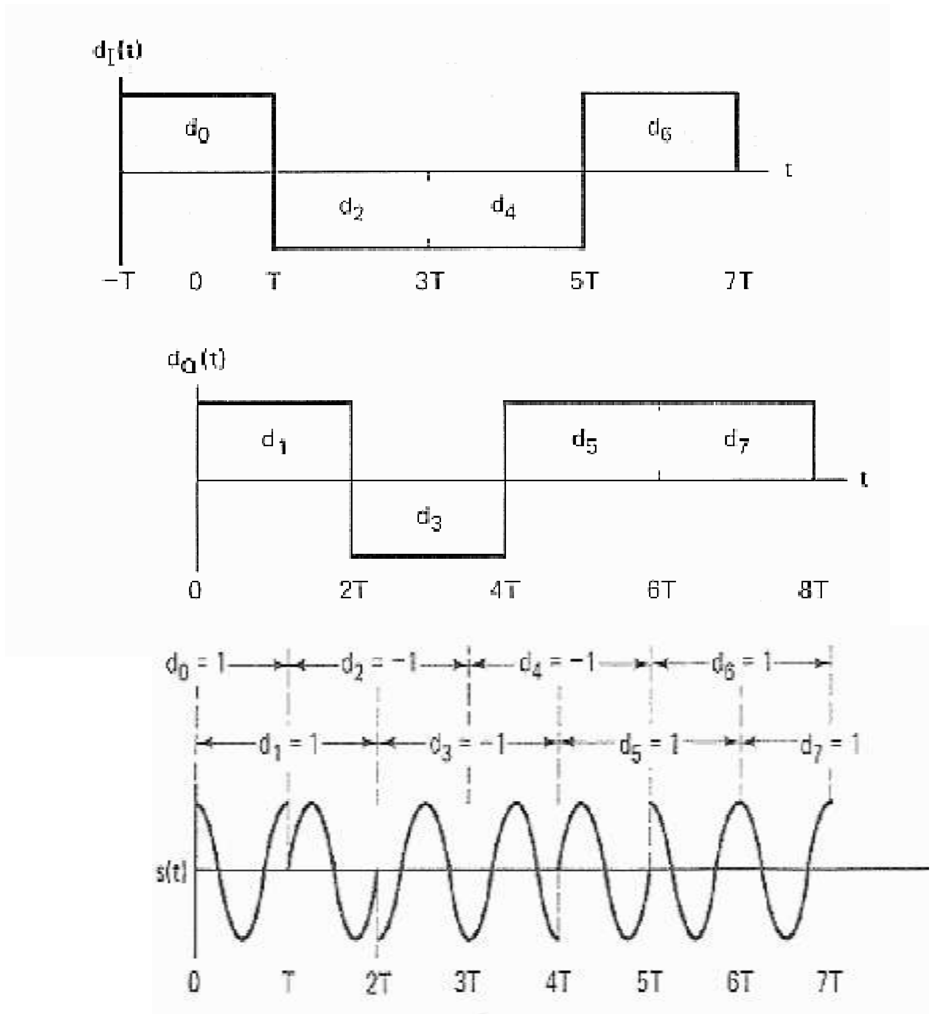
- **Offset quadrature phase-shift keying OQPSK** is a variant of Phase Shift Keying modulation using 4 different values of the phase to transmit. It is sometimes called **Staggered quadrature phase shift keying SQPSK** .
- **OQPSK** limits the phase-jumps that occur at symbol boundaries to no more than 90° and reduces the effects on the amplitude of the signal due to any low-pass filtering.





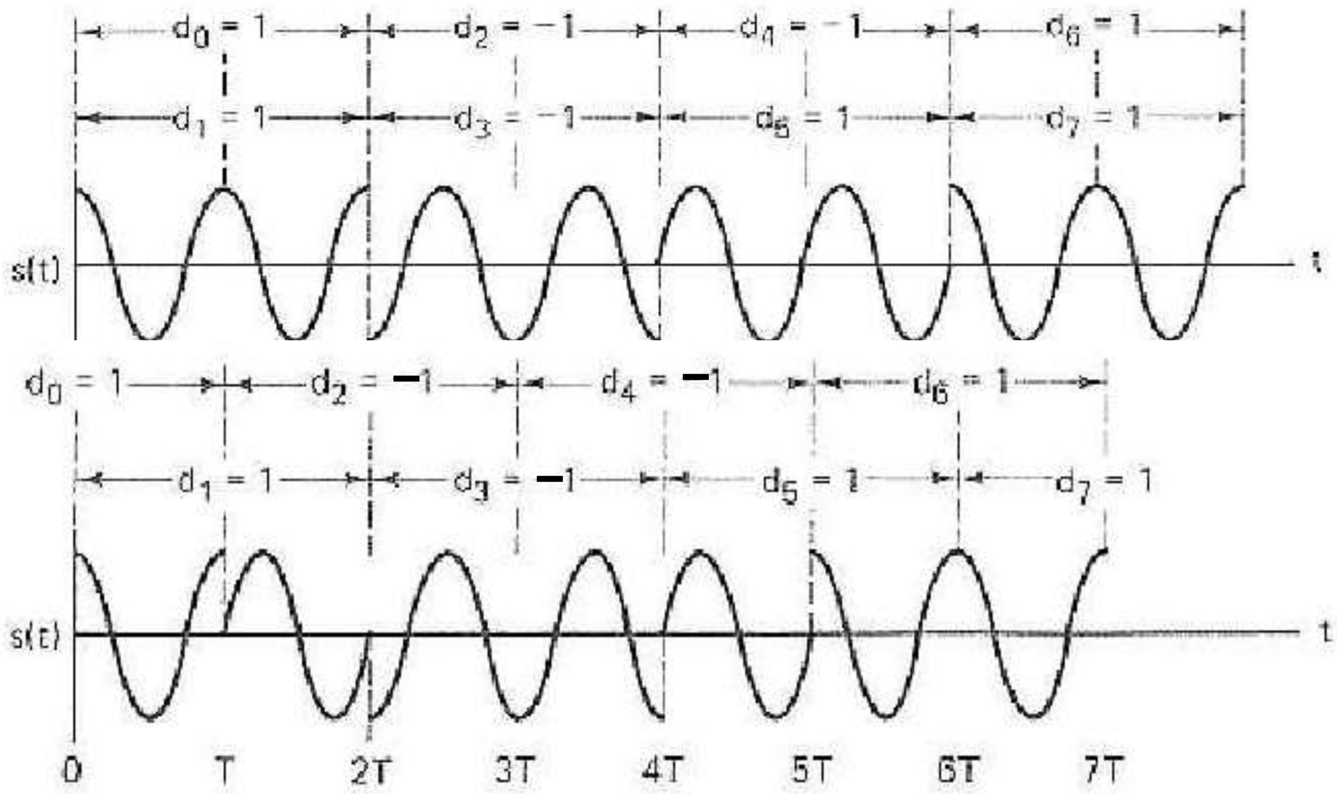
OPSK

If the two bit streams I and Q are offset by a 1/2 bit interval, then the amplitude fluctuations are minimised since the phase never changes by 180°. This modulation scheme, Offset Quadrature Phase shift Keying (OQPSK) is obtained from QPSK by delaying the odd bit stream by half a bit interval with respect to the even bit stream.



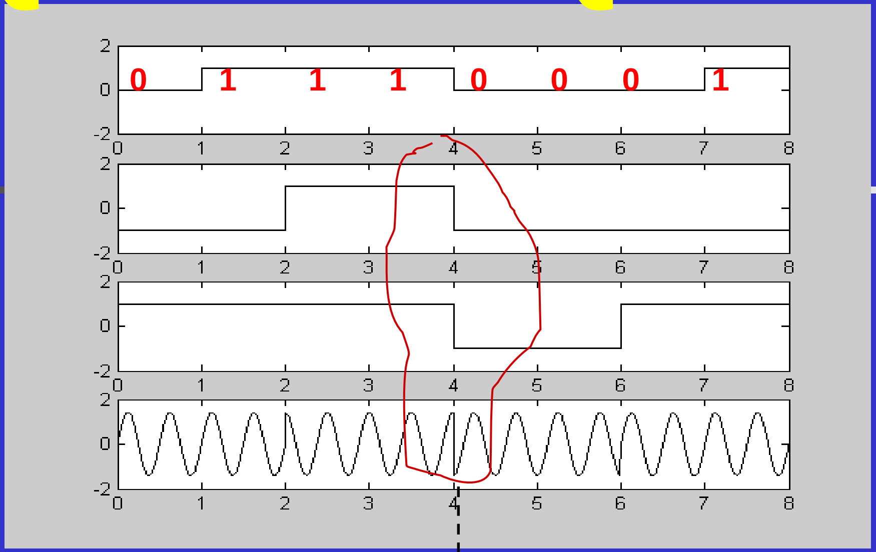
(b) OQPSK

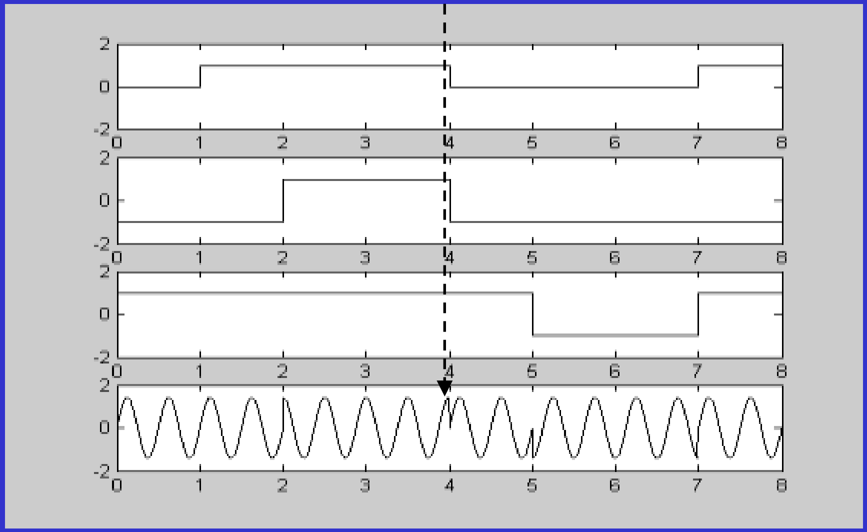
QPSK vs. OQPSK

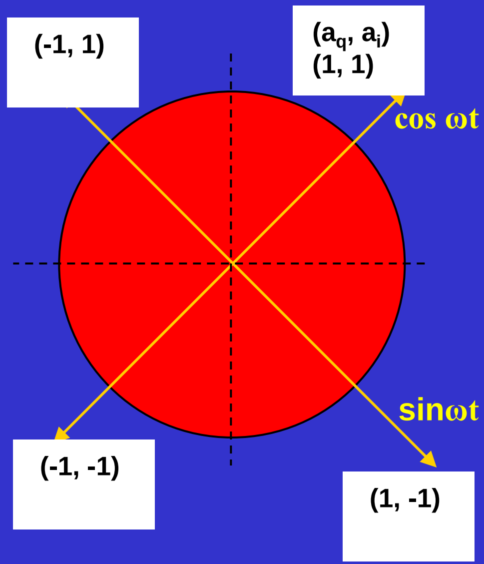


(b) OQPSK

QPSK & OQPSK







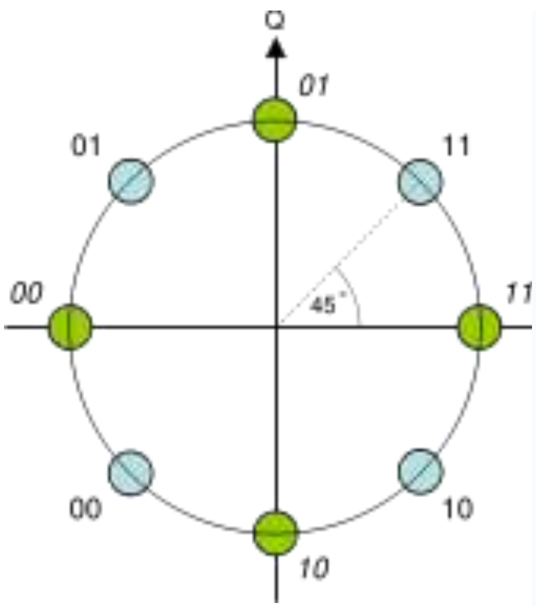
Disadvantages of OQPSK

(1) OQPSK introduces a delay of half a symbol into the demodulation process. In other words, using OQPSK increases the temporal efficiency of normal QPSK.

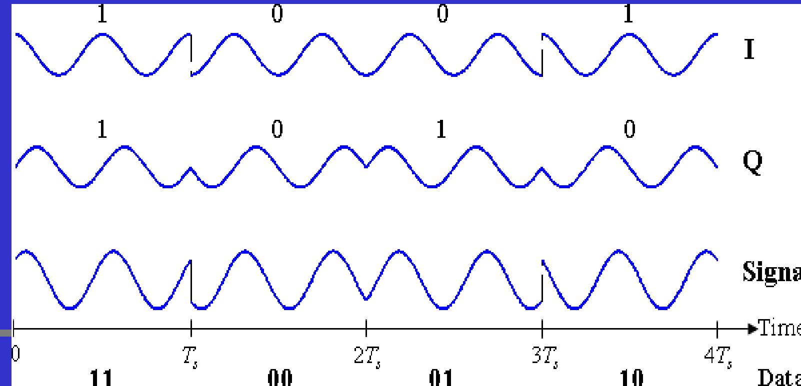
➔ The reason is that the in phase and quadrature phase components of the OQPSK cannot be simultaneously zero. Hence, the range of the fluctuations in the signal is smaller.

(2) An additional disadvantage is that the quiescient power is nonzero, which may be a design issue in devices targeted for low power applications.

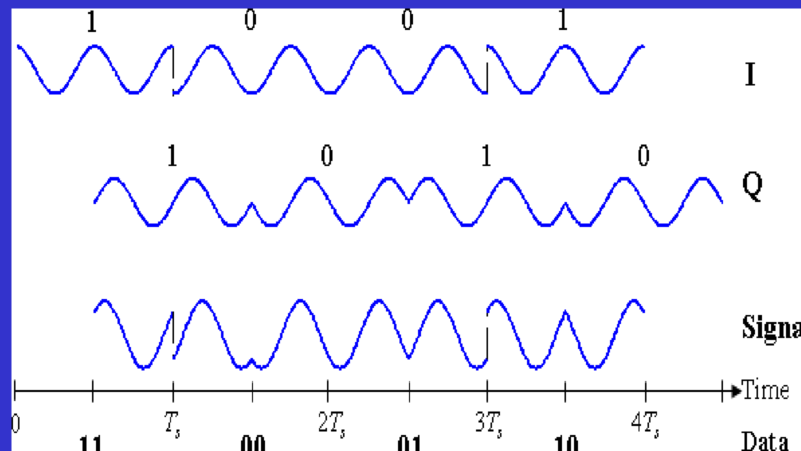
QPSKπ/4-



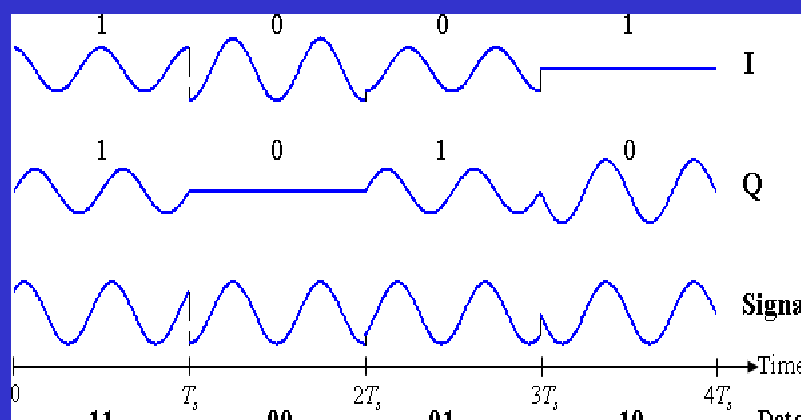
Dual constellation diagram for π/4-QPSK. This shows the two separate constellations with identical Gray coding but rotated by 45° with respect to each other.
This final variant of QPSK uses two identical constellations which are rotated by 45° (π / 4 radians, hence the name) with respect to one another. Usually, either the even or odd data bits are used to select points from one of the constellations and the other bits select points from the other constellation. This also reduces the phase-shifts from a maximum of 180°, but only to a maximum of 135° and so the amplitude fluctuations of π / 4–QPSK are between OQPSK and non-offset QPSK.



QPSK



OQPSK



π/4-QPSK

Minimum Shift Keying (MSK)

- It is a special type of continuous phase-frequency shift keying (CPFSK).
- The peak frequency deviation is equal to 1/4 the bit rate.
- MSK has a modulation index of 0.5 .

$$K_{MSK} = 2\,\Delta F / R_b$$

- The name Minimum Shift Keying (MSK) implies the minimum frequency separation that allows orthogonal detection as two FSK signals $V_H(t)$ & $V_L(t)$.

$$\int_0^T V_H(t)V_L(t)dt = 0$$

- MSK is a spectrally efficient modulation scheme and is particularly attractive for use in mobile communication systems because of its possesses properties such as :
  - constant envelope.
  - Spectral efficiency.
  - Good BER performance.
  - Self-synchronizing capability.

MSK

MSK uses changes in phase to represent 0's and 1's, but unlike most other keying, the pulse sent to represent a 0 or a 1, not only depends on what information is being sent, but what was previously sent. The pulse used in MSK is the following:

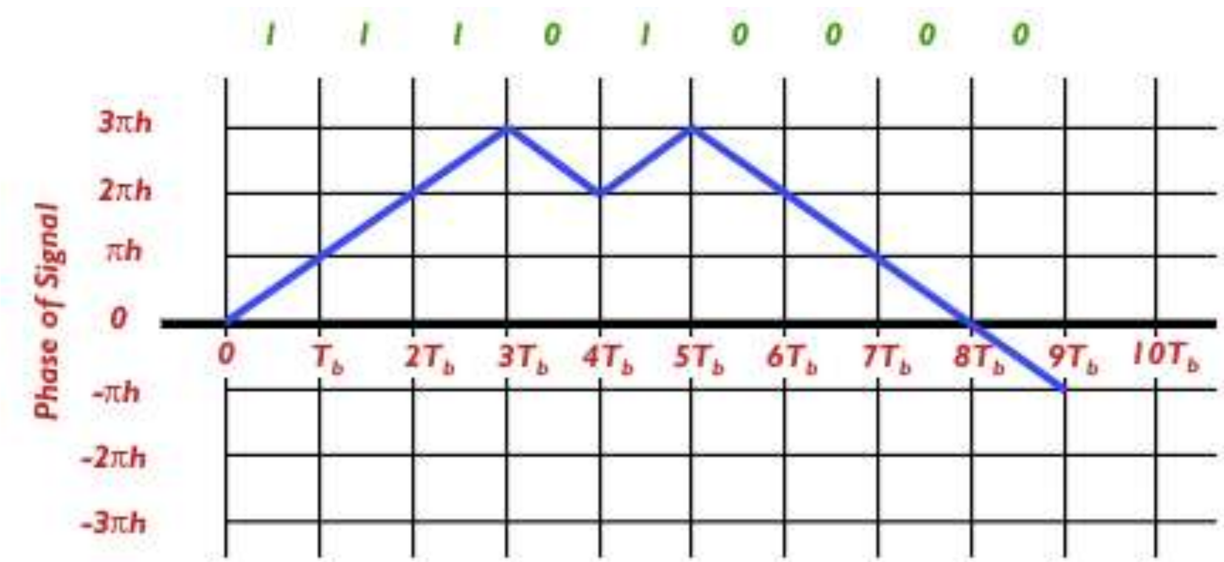
$$s(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \theta(t))$$

where

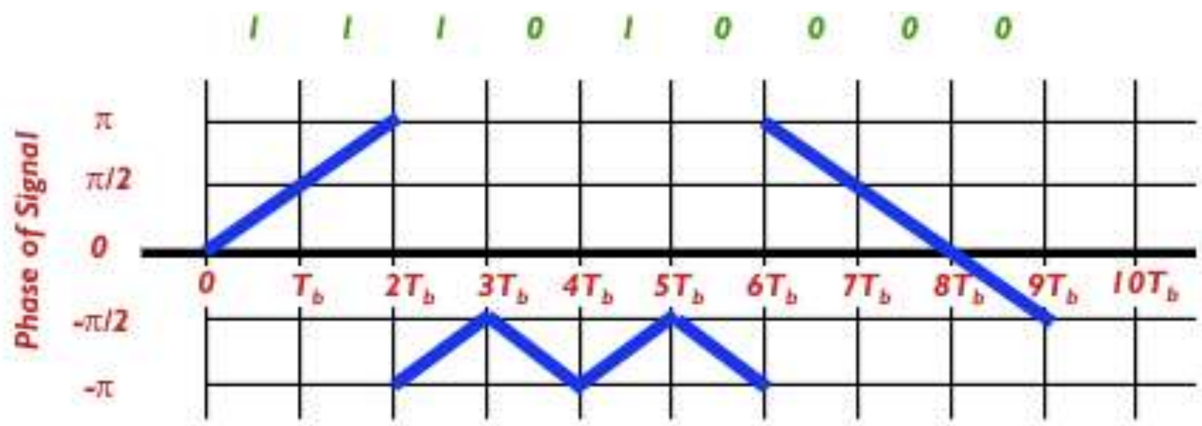
$$\theta(t) = \theta(0) + \frac{\pi h}{T_b}$$ if a '1' was sent

$$\theta(t) = \theta(0) - \frac{\pi h}{T_b}$$ if a '0' was sent

● Right from the equation we can see that θ(t) depends not only from the symbol being sent (from the change in the sign), but it can be seen that is also depends on θ(0) which means that the pulse also depends on what was previously sent. To see how this works let's work through an example. Assume the data being sent is 111010000, then the phase of the signal would fluctuate as seen in the figure below.



● If it assumed that h = 1/2, then the figure simplifies. The phase can now go up or down by increments of pi/2, and the values at which the phase can be (at integer intervals of Tb) are {-pi/2, 0, pi/2, pi}. The above example now changes to the graph below. The figure illustrates one feature of MSK that may not be obvious, when a large number of the same symbol is transmitted, the phase does not go to infinity, but rotates around 0 phase.



- An MSK signal can be thought of as a special form of OQPSK where the baseband rectangular pulses are replaced with half-sinusoidal pulses.

$$S_{MSK}(t)=\sum_{i=0}^{N-1} m_{Ii}(t)p(t-2iT_b)\cos 2\pi f_c t+\sum_{i=0}^{N-1} m_{Qi}(t)p(t-2iT_b-T_b)\sin 2\pi f_c t.$$

where

$$\mathbf{P(t)} = \begin{cases} \cos(\pi t/2T_b) & 0<t<2T_b \\ 0 & \text{elsewhere} \end{cases}$$

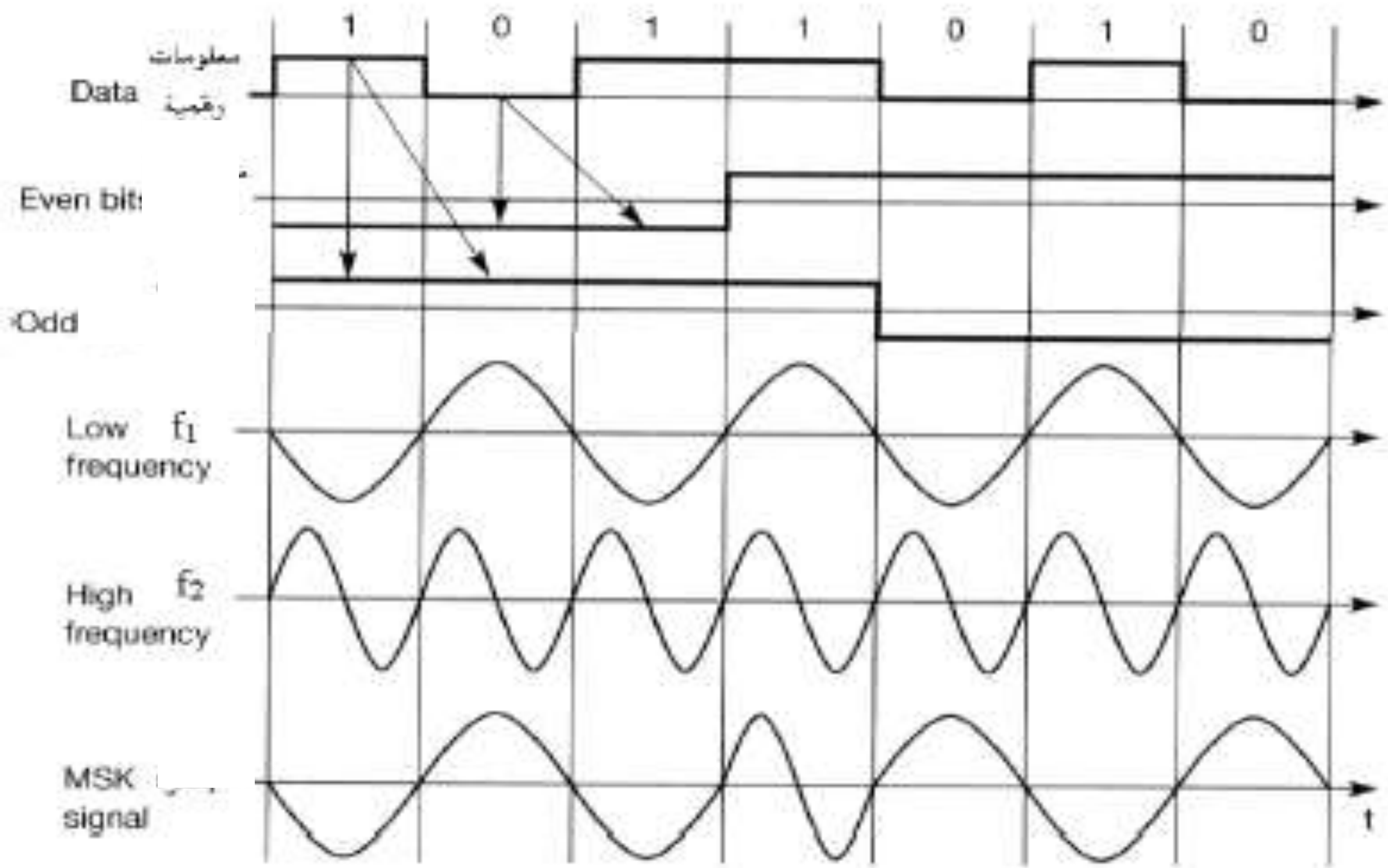
MSK better than QPSK

Even though the derivation of MSK was produced by analyzing the changes in phase, MSK is actually a form of frequency-shift-keying (FSK) with

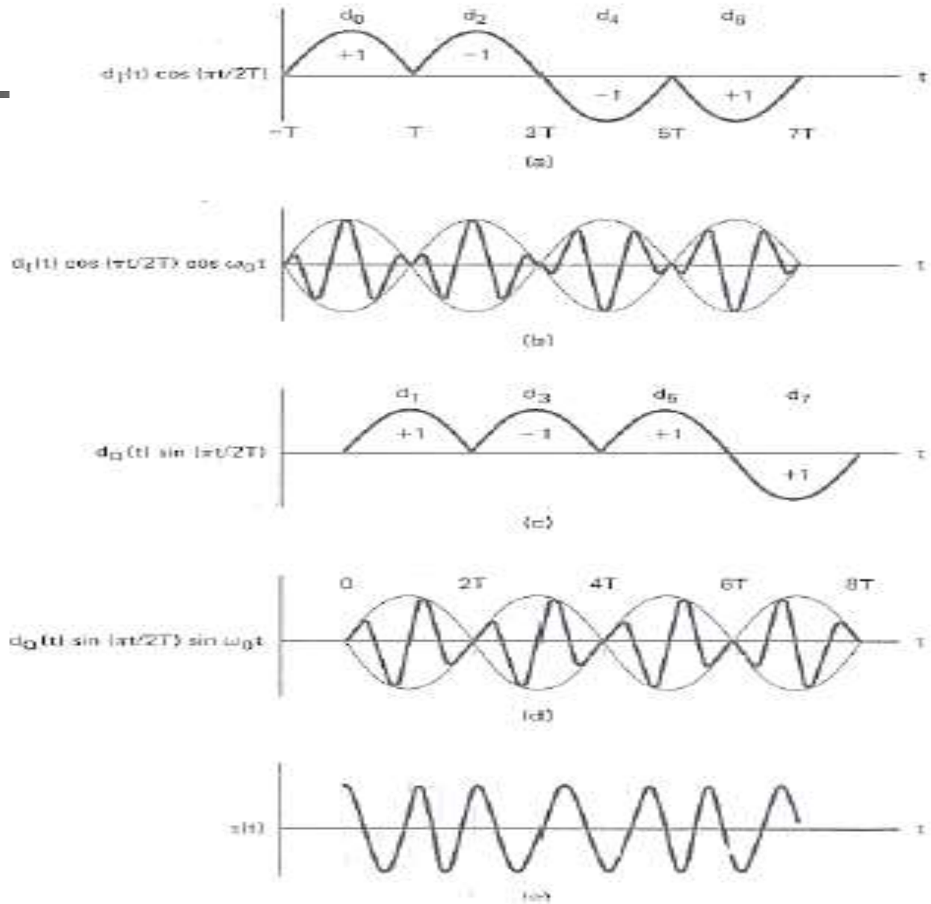
$$f_c = \frac{1}{2}(f_1 + f_2) \qquad\qquad h = T_b(f_1 - f_2)$$

(where f1 and f2 are the frequencies used for the pulses). MSK produces an FSK with the minimum difference between the frequencies of the two FSK signals such that the signals do not interfere with each other. MSK produces a power spectrum density that falls off much faster compared to the spectrum of QPSK. While QPSK falls off at the inverse square of the frequency, MSK falls off at the inverse fourth power of the frequency. Thus MSK can operate in a smaller bandwidth compared to QPSK.

Generating minimum-shift keying



MSK



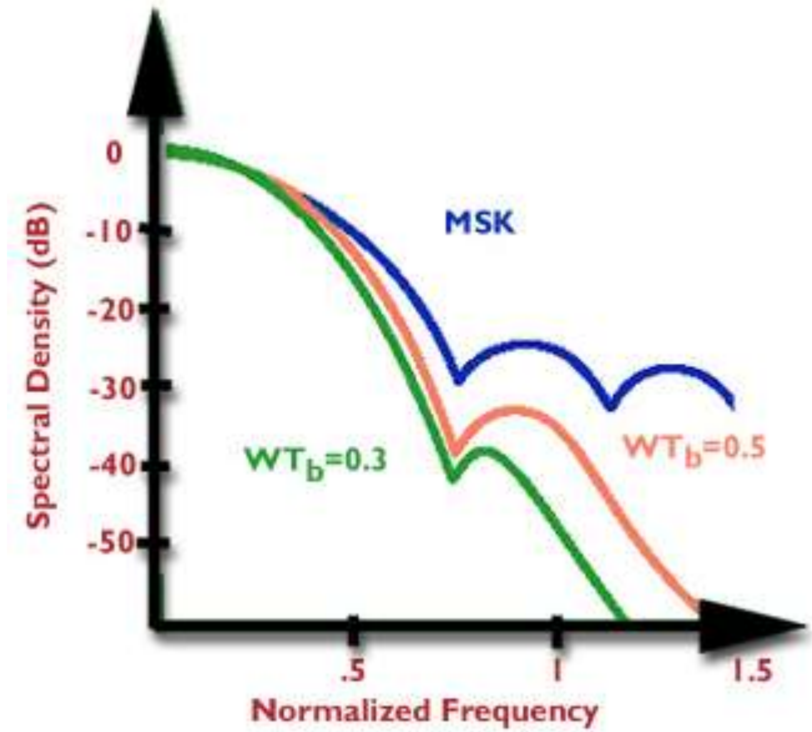
d_0
d_2
d_4
d_6
+1
−1
−1
+1
d_I(t) cos (πt/2T)
t
−T
T
3T
5T
7T
(a)
d_I(t) cos (πt/2T) cos ω_0t
t
(b)
d_1
d_3
d_5
d_7
+1
−1
+1
+1
d_Q(t) sin (πt/2T)
t
(c)
0
2T
4T
6T
8T
d_Q(t) sin (πt/2T) sin ω_0t
t
(d)
s(t)
t

Gaussian Minimum Shift Keying GMSK

Even though MSK's power spectrum density falls quite fast, it does not fall fast enough so that interference between adjacent signals in the frequency band can be avoided. To take care of the problem, the original binary signal is passed through a Gaussian shaped filter before it is modulated with MSK.

Frequency Response:

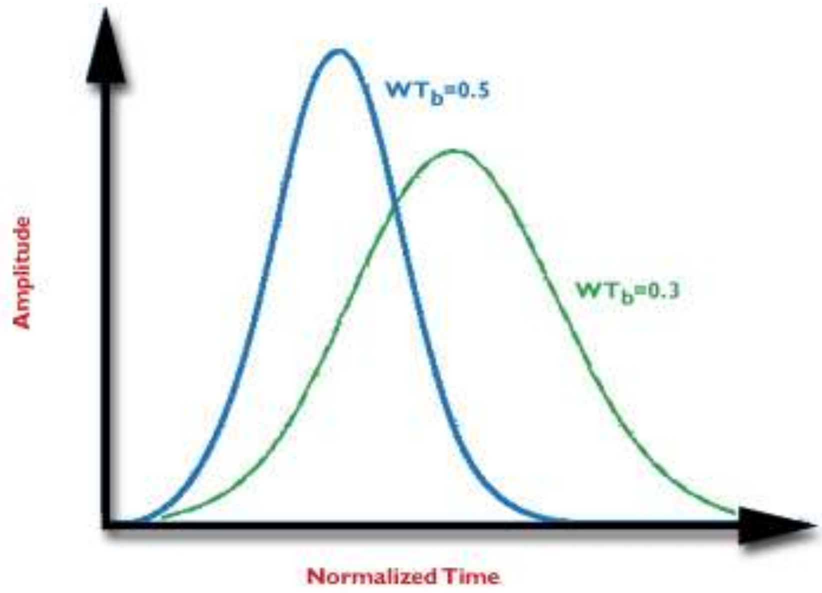
The principle parameter in designing an appropriate Gaussian filter is the time-bandwidth product WTb. Please see the following figure for the frequency response of different Gaussian filters. Note that MSK has a time-bandwidth product of infinity.



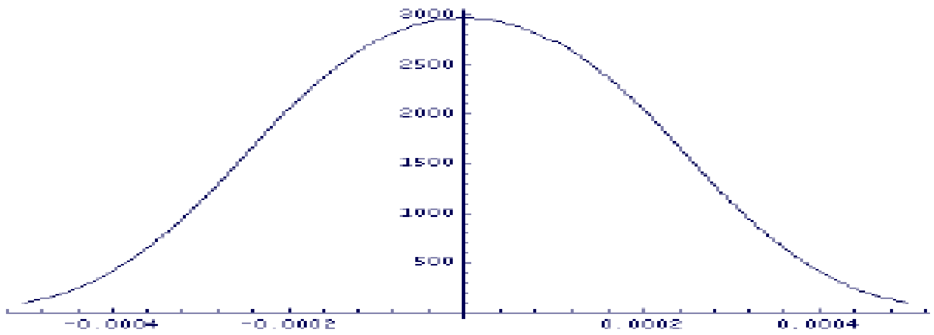
As can be seen from above, GMSKs power spectrum drops much quicker than MSK's. Furthermore, as WTb is decreased, the roll-off is much quicker.

Time-Domain Response:

Since lower time-bandwidth products produce a faster power-spectrum roll-off, why not have a very small time-bandwidth product. It happens that with lower time-bandwidth products the pulse is spread over a longer time, which can cause intersymbol interference.



Therefore as a compromise between spectral efficiency and time-domain performance, an intermediate time-bandwidth product must be chosen.



The truncated and scaled impulse response of the Gaussian low-pass filter.

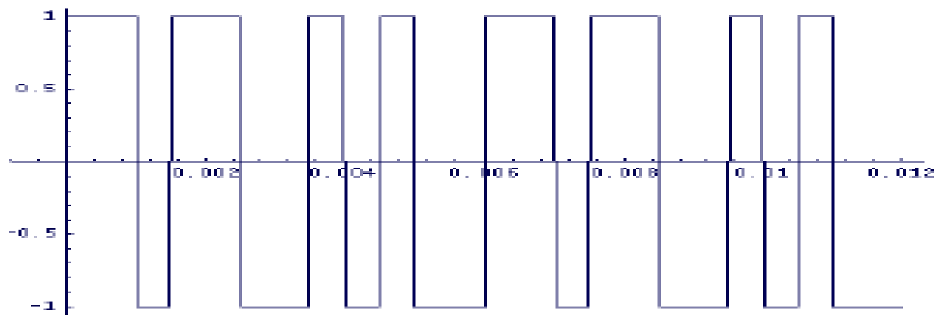
Ensuring that the response of the filter to a single 1 is a phase change of $\pi/2$, is equivalent to choosing the constant K to satisfy the following equation

$$\int_{-T}^{T} Kg(t)\,dt = \pi/2.$$

To demonstrate the modulation, we are using the following randomly chosen binary data stream. (This data stream repeats after 12 bits.)

{ 1,1,-1,1,1,-1,-1,1,-1,1,-1,-1, 1,1,-1,1,1,-1,-1,1,-1,1,-1,-1,............}.

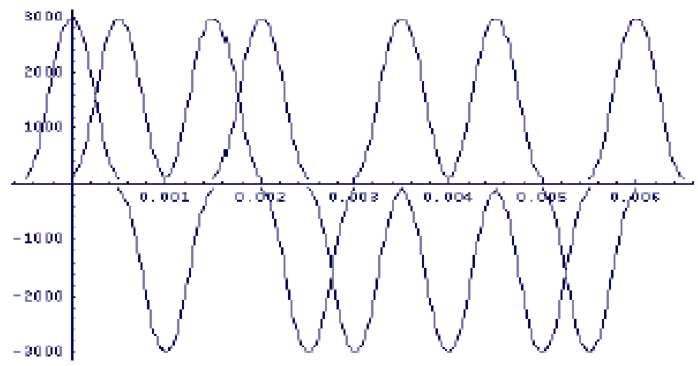
The beginning of this data stream can be represented graphically by the following



The beginning of the data stream being sent through the filter.

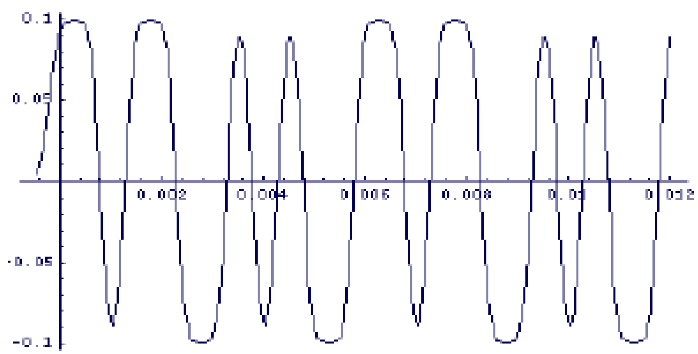
As the data passes through the filter it is shaped and ISI (inter symbol interference) is introduced since more than one bit is passing through the filter at any one time. For $B_N = 0.5$, since the bits are spread over two bit periods, the second bit enters the filter as the first is half way through, the third enters as the first leaves etc....

The first few Gaussian shaped pulses are represented graphically in the following figure.



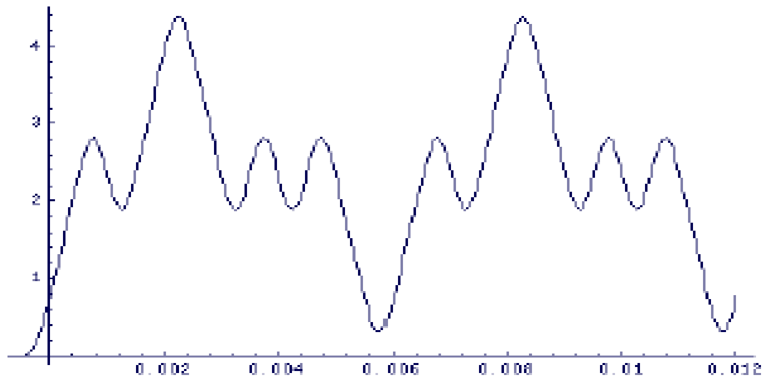
The individual shaped pulses representing the data stream.

These individual shaped pulses are then added together to give a function which is represented graphically in the following figure. This is the function denoted by b(t).



The function b(t) as in the second figure

This function, b(t), is then integrated, with respect to t (time) from t to ∞, to give the function c(t) as shown in the second figure. This function c(t) is represented graphically below.

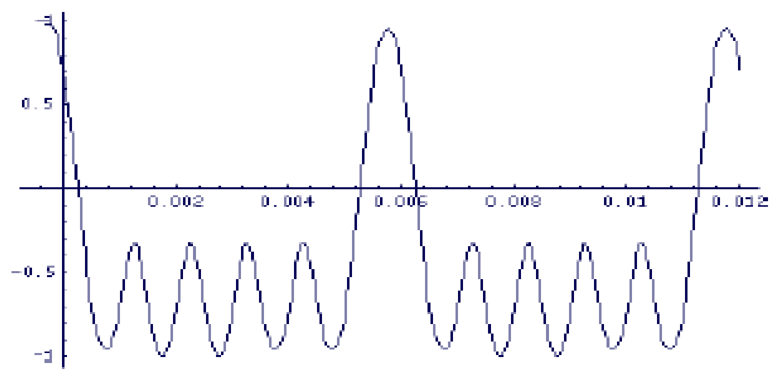


The function c(t) as in the second figure.

Once we have the function c(t), we take Sine and Cosine functions of it to produce the I and Q-baseband signals. Taking the Cosine of c(t) produces the I-baseband signal I(t) i.e.

$$I(t) = \mathrm{Cos}[\ c(t)\ ].$$

This function I(t) is represented graphically below.

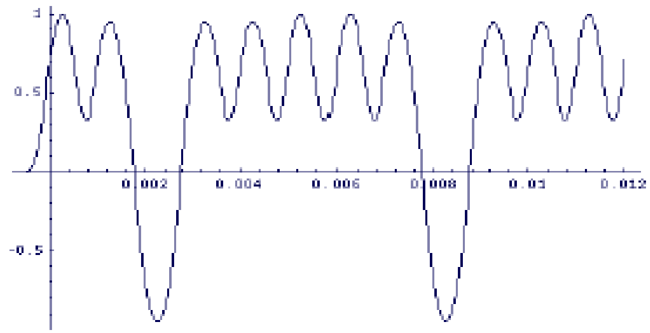


The I-baseband signal, i.e. the function I(t) as the second figure

Taking the Sine of c(t) produces the Q-baseband signal Q(t) i.e.

$$Q(t) = \mathrm{Sin}[\ c(t)\ ].$$

This function Q(t) is represented graphically below.



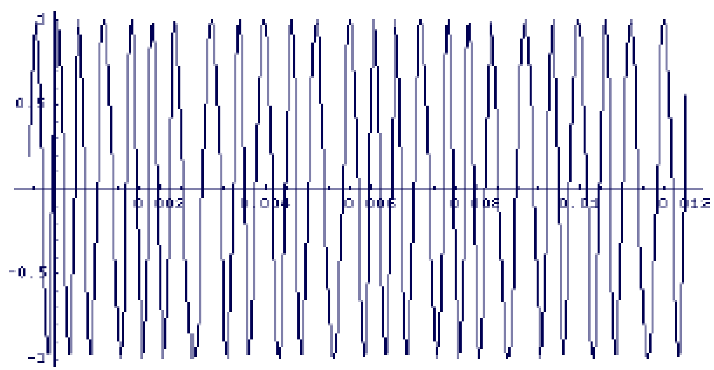
The Q-baseband signal, i.e. the function Q(t) as in the second figure.

These two functions I(t) and Q(t) are then passed through the I/Q modulator which leads to the output signal m(t) which can be written as

$$m(t) = \mathrm{Sin}(2\pi f_c\ t)\ I(t) + \mathrm{Cos}(2\pi f_c t)\ Q(t),$$

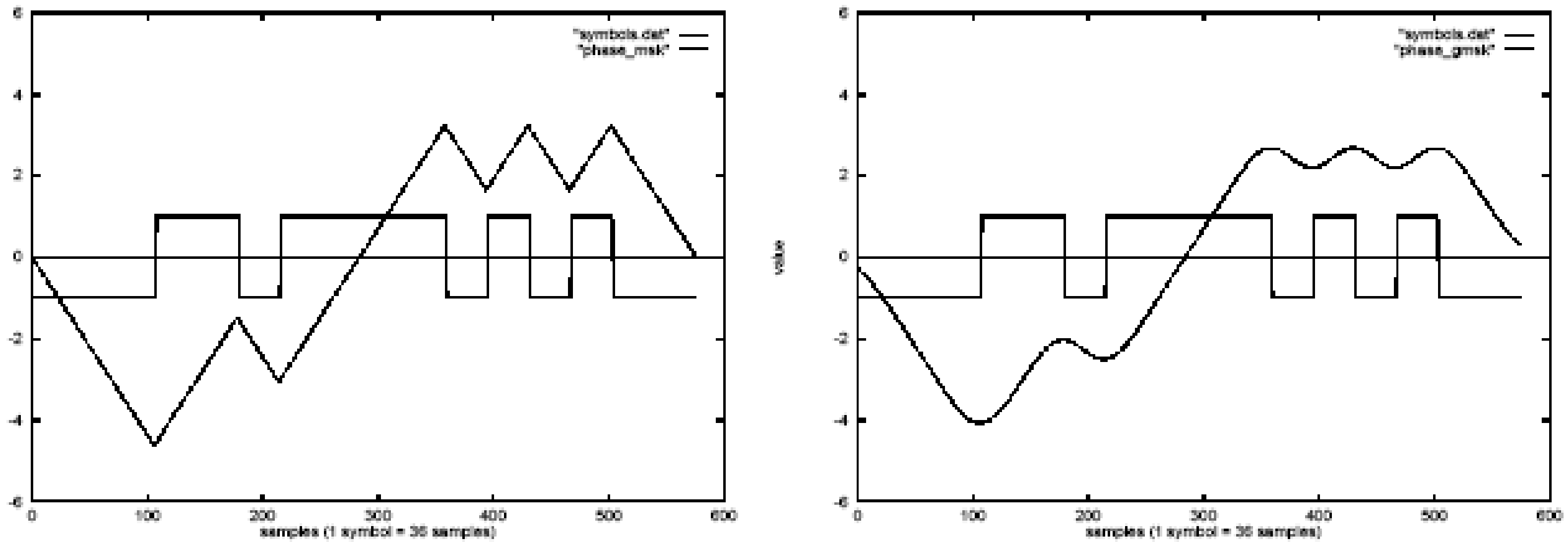
where f_c is the carrier frequency used as the oscillator in the second figure

The GMSK signal m(t) is represented

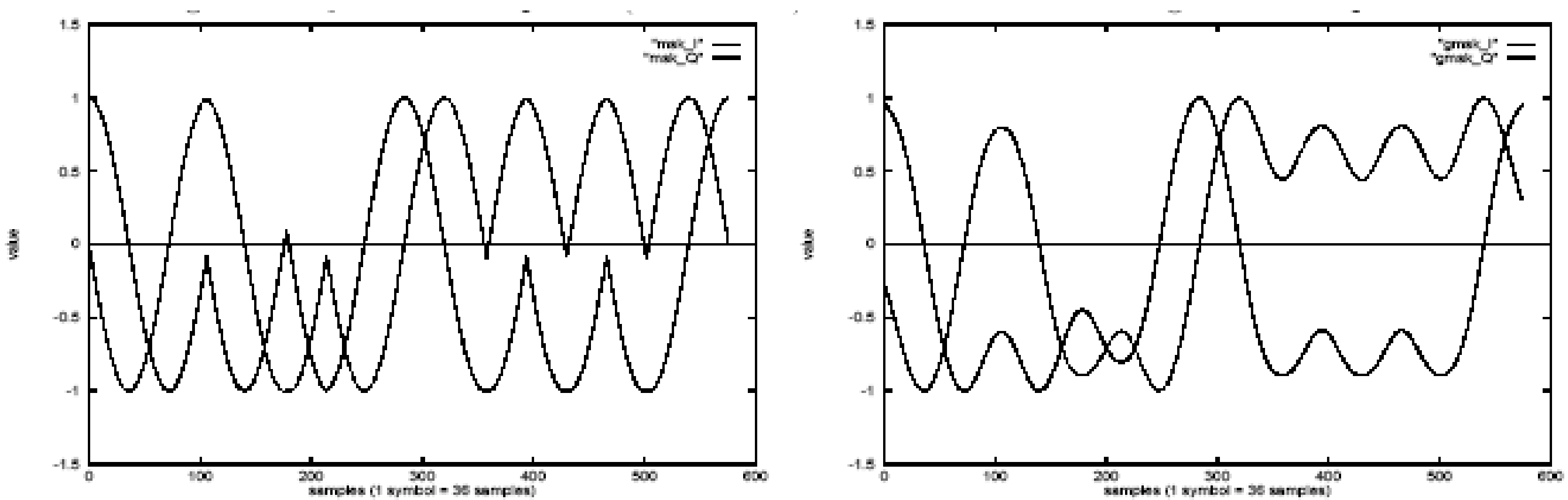


The GMSK modulated signal m(t) as in the second figure.

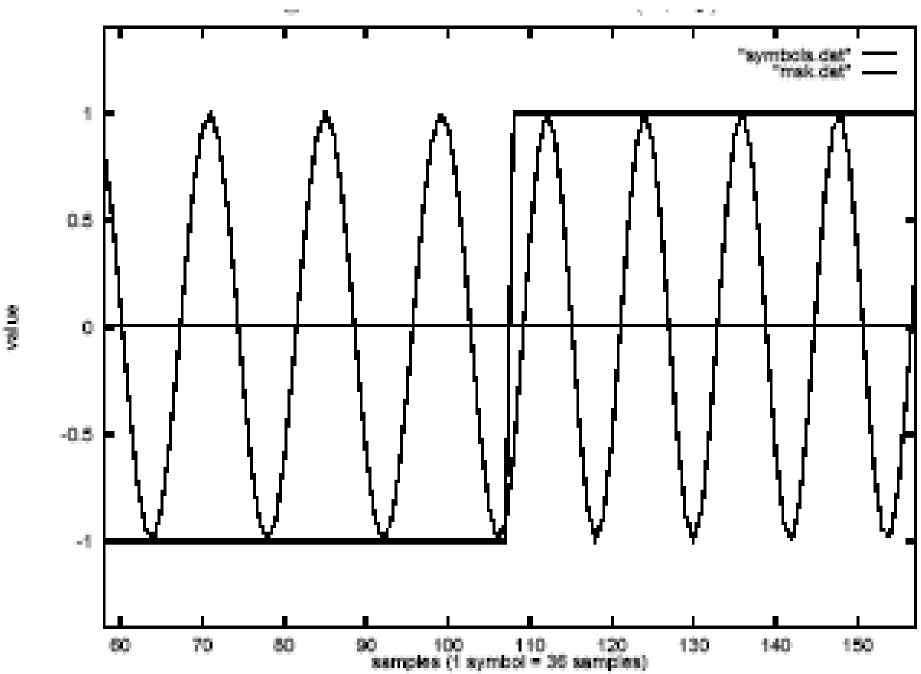
The figure shows the 16-bit NRZ (Non-Return-to-Zero) sequence (-1,-1,-1,+1,+1,-1,+1,+1,+1,+1,-1,+1,-1,+1,-1,-1) and the corresponding phase trajectory of MSK (left) and GMSK (right) signals. The phase increment per symbol is $\pm\frac{\pi}{2}$ for the MSK signal.

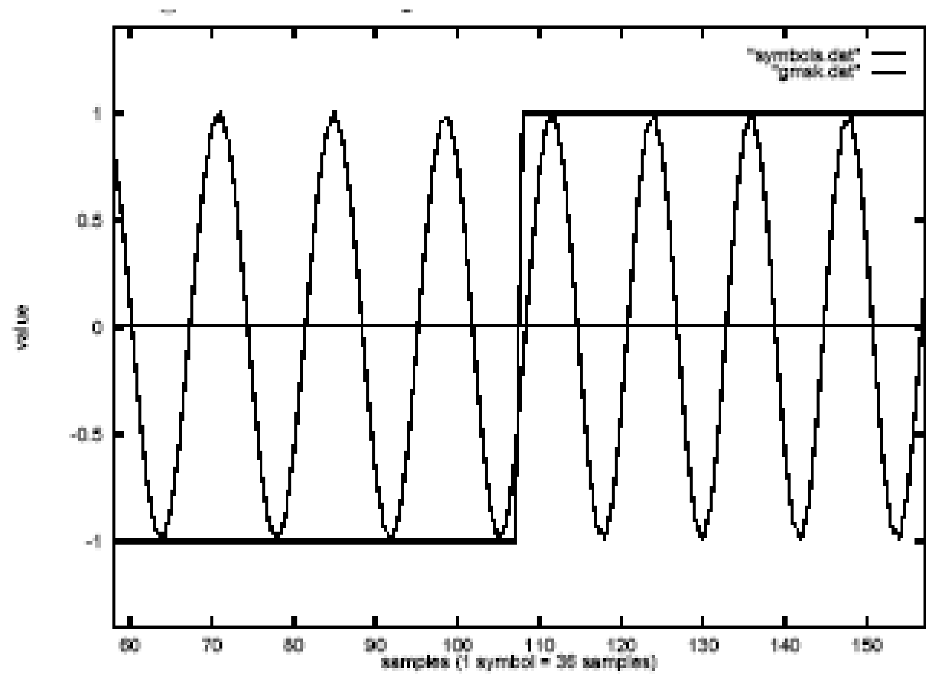


The figure shows the in phase I (real) and quadrature Q (imaginary) components of the MSK (left) and GMSK (right) corresponding base band equivalent signals.



- The figure shows the MSK and GMSK modulated signals for two different symbols.
- <u>Notice</u> the slight difference of frequency between the modulated signal of symbol (-1) and symbol (1). This shows the FM nature of MSK and GMSK signals.





The reliability of a data message produced by a GMSK system is highly dependent on the following:

(1) Receiver thermal noise: this is produced partly by the receive antenna and mostly by the radio receiver.

(2) Channel fading: this is caused by the multipath propagation nature of the radio channel.

(3) Band limiting: This is mostly associated with the receiver If frequency and phase characteristics

(4) DC drifts: may be caused by a number of factors such as temperature variations, asymmetry of the frequency response of the receiver, frequency drifts of the receiver local oscillator.

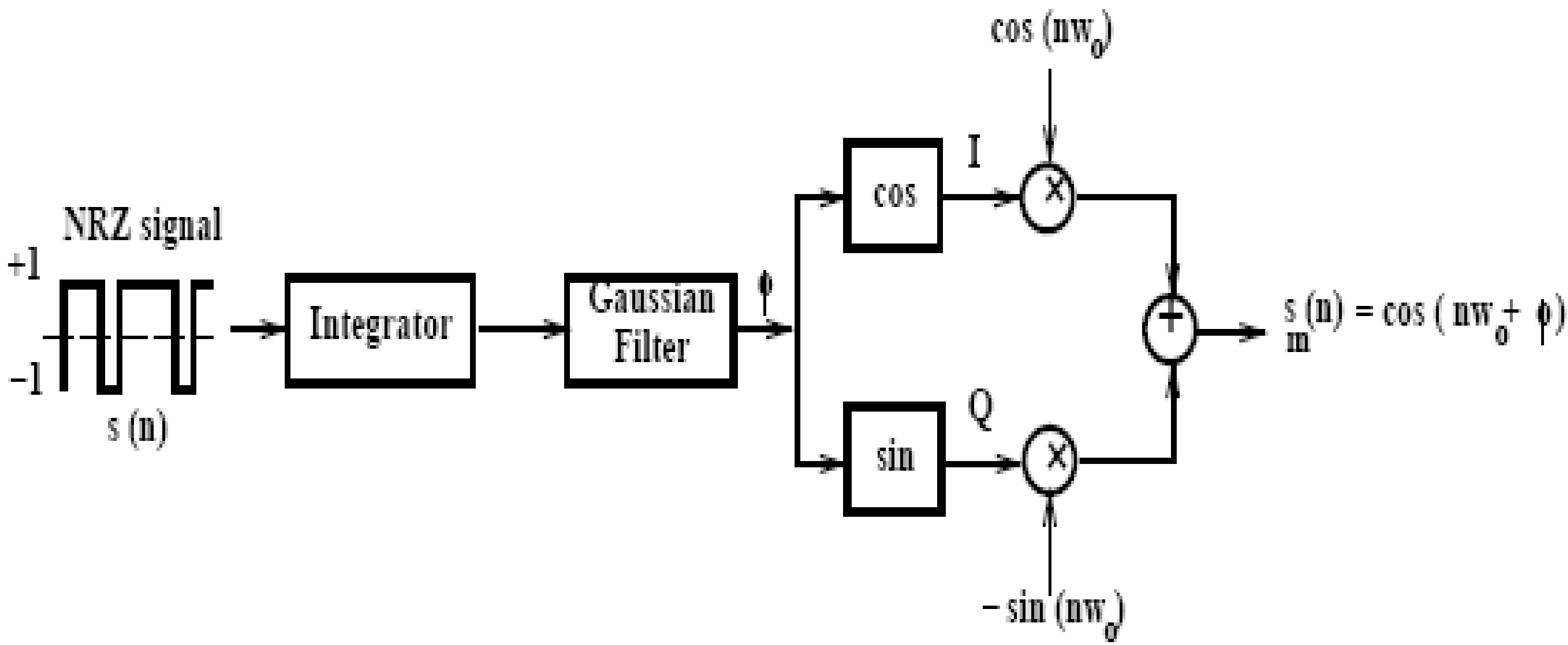
(5)Frequency offset:

* This refers to the receiver carrier frequency drift relative to the frequency transmitted caused by the finite stability of all the frequency sources in the receiver. The shift is also caused partly by Doppler shifts, which result due to the relative transmitter/receiver motion.
* The frequency offset causes the received IF signal to be off-center with respect to the IF filter response, and this cause more signal distortion.
* The frequency offset also results in a proportional DC component at the discriminator output.

(6)Timing errors:

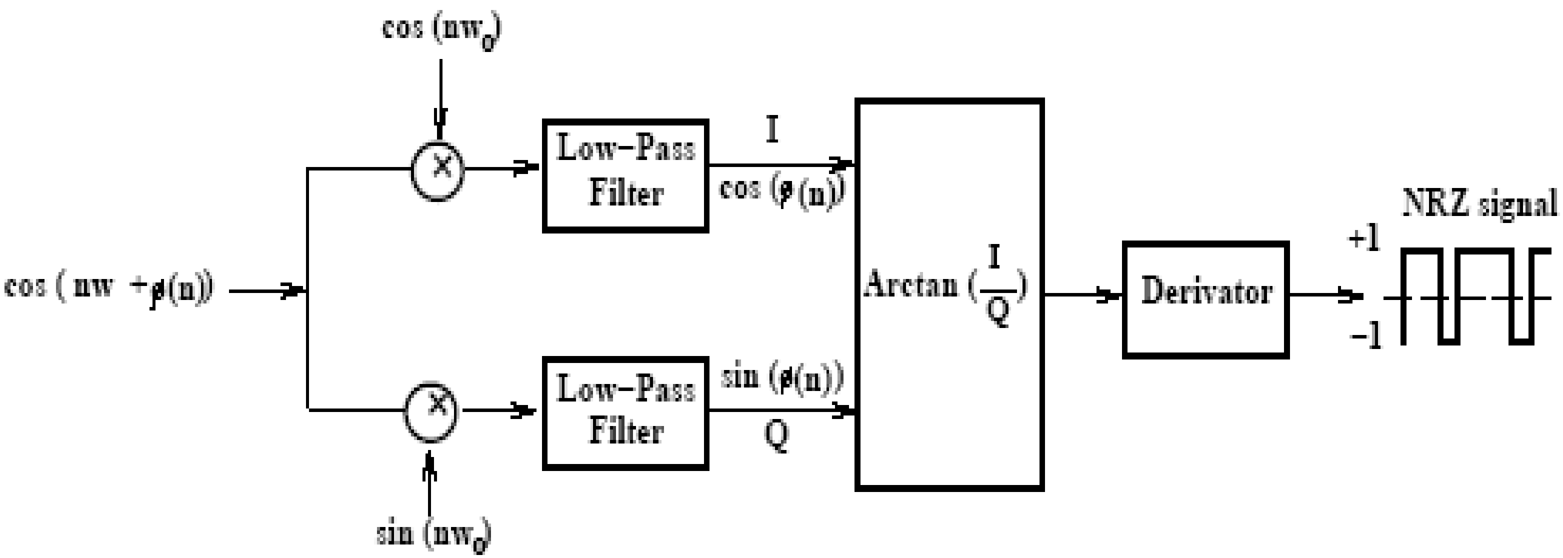
- The timing reference causes the sampling instants to be offset from the center of the transmit eye.
- As GMSK is a filtered version of MSK, this introduces another variable that can be used to describe the exact nature of the GMSK modulation.
- This variable is referred to as the BT, where B is the 3dB point of the Gaussian filter, and T is the bit duration. Therefore a BT of infinity would relate to MSK.
- The smaller the BT the smaller the spectral density however this comes at a trade off of increased inter-symbol interference.
- This is because by smoothing the edges of the bit pulses they begin to overlap each other. The greater the smoothing, the greater the overlapping, until eventually individual bits may be undetectable.

How to implement a GMSK modulator?



GMSK modulation block diagram

How to implement a GMSK demodulator?



GSM Modulation Specifications

In the GSM standard, Gaussian Minimum Shift Keying with a time-bandwidth product of 0.3 was chosen as a compromise between spectral efficiency and intersymbol interference. With this value of WTb, 99% of the power spectrum is within a bandwidth of 250 kHz, and since GSM spectrum is divided into 200 kHz channels for multiple access, there is very little interference between the channels. The speed at which GSM can transmit at, with WTb=0.3, is 271 kb/s. (It cannot go faster, since that would cause intersymbol interference).

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