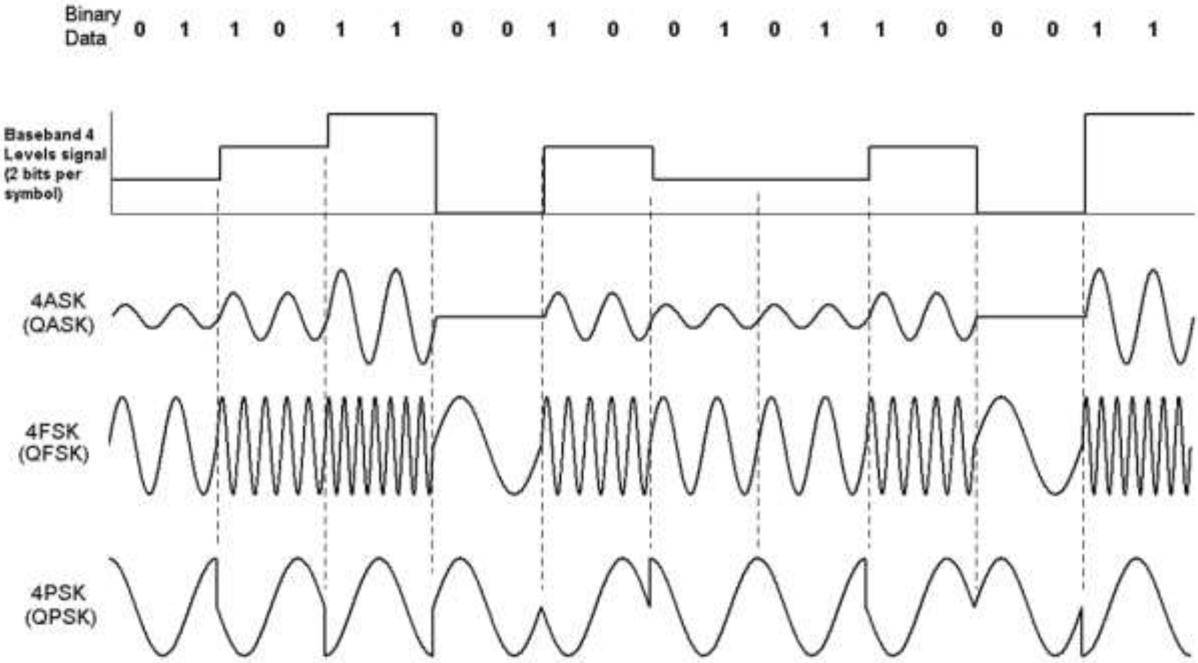
2.6 MODULATION TECHNIQUES WITH INCREASED SPECTRAL EFFICIENCY

In addition to the reliability and the low P_E, the efficient usage of the bandwidth is an important aspect in the design of digital communication systems.

As we know, the best design is to transmit the maximum information rate through the minimum possible bandwidth. We defined earlier the spectral efficiency Γ. To make Γ as large as possible, we can:

- Decrease B by filtering the transmitted signal prior to the transmission. *How far is this method useful?*
- Increase the number of transmitted bits per second (R), but we must consider the Shannon-Hartley limit of channel capacity. So, to avoid ISI, $T_0 B \geq 0.5$ for baseband signals, and $T_0 B \geq 1$ for Bandpass signals.
- The final option: increase M (i.e. increase the number of bits per a transmitted symbol). Practical systems currently exist with M of 4, 8, 16, … 1024.

The multi-level per symbol (*M-symbol*) signaling for the studied digital modulations will referred as: MASK, MFSK and MPSK.



In practice, only MPSK and QAM are used, because:

- the increase of M in MASK results in level ambiguity at detection. The channel effects like the noise and distortion make the process of the detection very hard. Nevertheless, increasing M, undoubtedly, increases P_E. But it is still acceptable for small M through good channels.

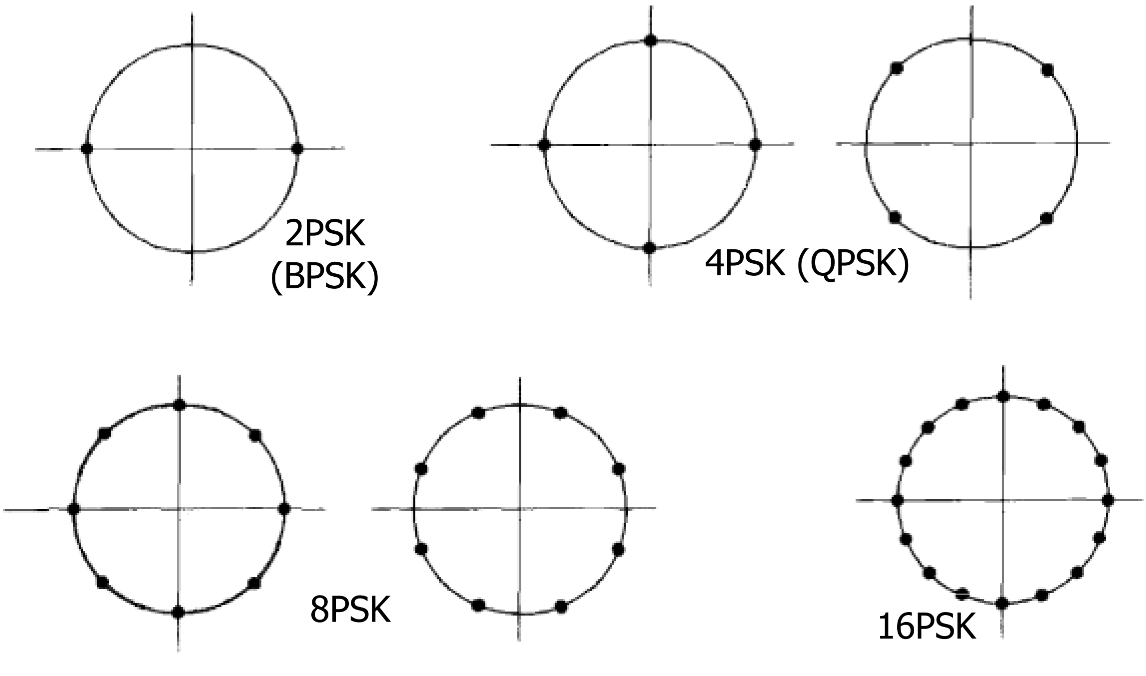
- as we studied before, the increase of M in MFSK requires larger bandwidth to accommodate the modulated signal, which decreases Γ.

2.6.1 M-Symbol Phase Shift Keying (MPSK)

MPSK implies the extension of the number of the allowed phasor states from 2 to 4, 8, 16……2^m. i.e. while the carrier amplitude being constant, the phase is changing according to the input taking one of the designed phase state.

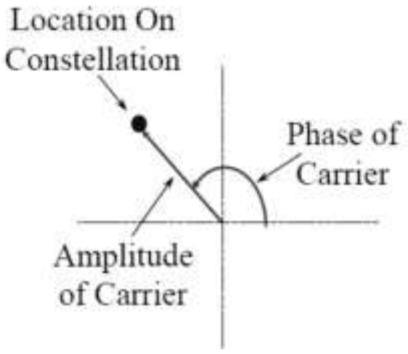
$$\text{MPSK} = \cos(\omega_c t + \theta_k) \quad \text{where } k = 0, 1, 2, \dots M-1 \quad , \qquad \theta_k = \frac{2\pi k}{M} \quad \text{or} \quad \theta_k = \frac{(2k+1)\pi}{M}$$

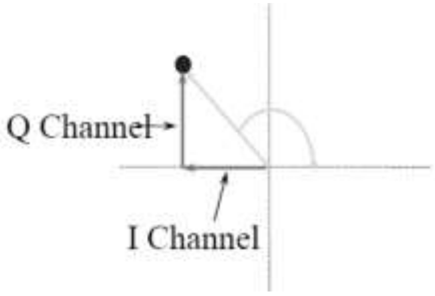
Some examples on MPSK is shown in the following figure:



Quadrature Modulation

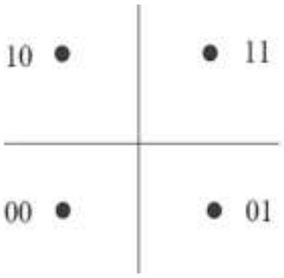
The phase and amplitude of the carrier at any given time determine the location on the Constellation. The amplitudes of the I and Q channels are derived from the rectangular coordinates of the carrier's amplitude and phase.

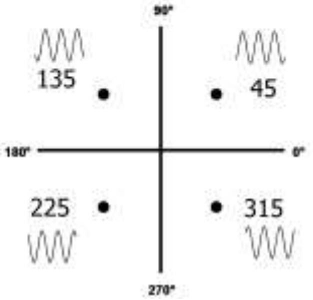




Quadri-phase-Shift Keying (QPSK)

Here, we study the coherent QPSK as an example of MPSK. In QPSK, as with BPSK, information carried by the transmitted signal is contained in the phase. The phase of the carrier takes on one of four equally spaced values, as:





For this set of values, we may define the transmitted signal as:

$$s(t) = \sqrt{2}\cos\left[2\pi f_c t + \frac{(2i-1)\pi}{4}\right] \qquad \text{where } i = 1,2,3,4$$

$$= \sqrt{2}\cos\left[\frac{(2i-1)\pi}{4}\right]\cos\omega_c t - \sqrt{2}\sin\left[\frac{(2i-1)\pi}{4}\right]\sin\omega_c t$$

Based on this representation, we can make the following observations

- There are two orthogonal basis functions, defined by a pair of quadrature carriers:

$$\phi_x = \cos\omega_c t \quad and \quad \phi_y = \sin\omega_c t$$

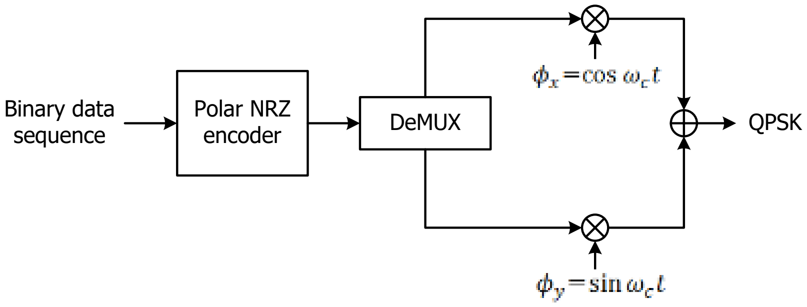
- There are four message points, and the associated signal vectors are defined by:

$$s = \begin{bmatrix} s_x \\ s_y \end{bmatrix} = \begin{bmatrix} \sqrt{2}\cos\left[\frac{(2i-1)\pi}{4}\right] \\ -\sqrt{2}\sin\left[\frac{(2i-1)\pi}{4}\right] \end{bmatrix} \qquad \text{where } i = 1,2,3,4$$

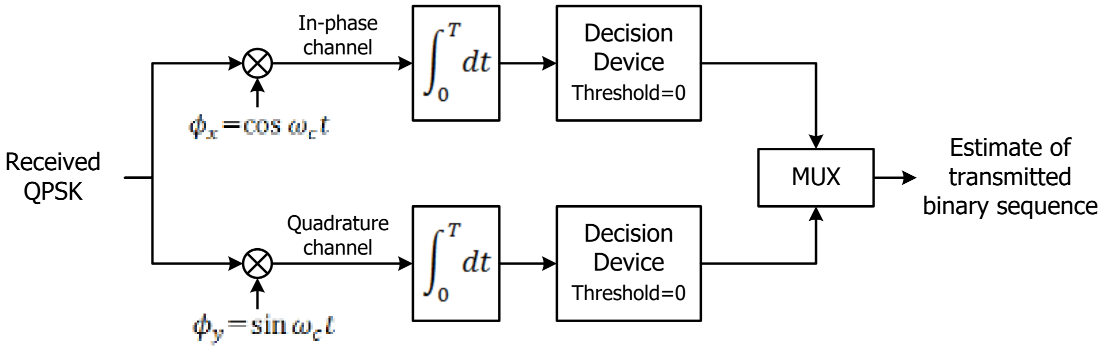
The elements of the signal vectors have their values summarized in the table below:

i	Gray-encoded input Di-bits	Phase of QPSK signal (rad)	Coordinates of Message points	
			s_x	s_y
1	10	$\pi/4$	$+1$	$+1$
2	00	$3\pi/4$	-1	$+1$
3	01	$5\pi/4$	-1	-1
4	11	$7\pi/4$	$+1$	-1

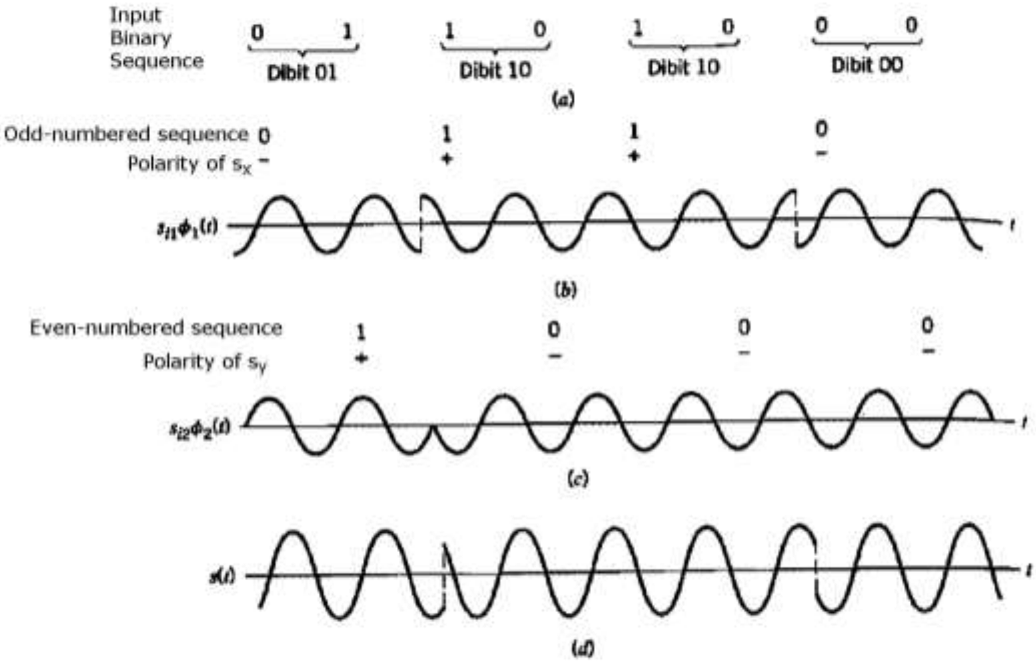
Modulator *



Demodulator *



The figure below illustrates the sequences and waveforms involved in the generation of a QPSK signal.


Input Binary Sequence
0 1
Dibit 01
1 0
Dibit 10
1 0
Dibit 10
0 0
Dibit 00
(a)
Odd-numbered sequence 0 1 1 0
Polarity of s_x − + + −
$s_{i1}\phi_1(t)$
t
(b)
Even-numbered sequence 1 0 0 0
Polarity of s_y + − − −
$s_{i2}\phi_2(t)$
t
(c)
$s(t)$
t
(d)