Constellation diagram

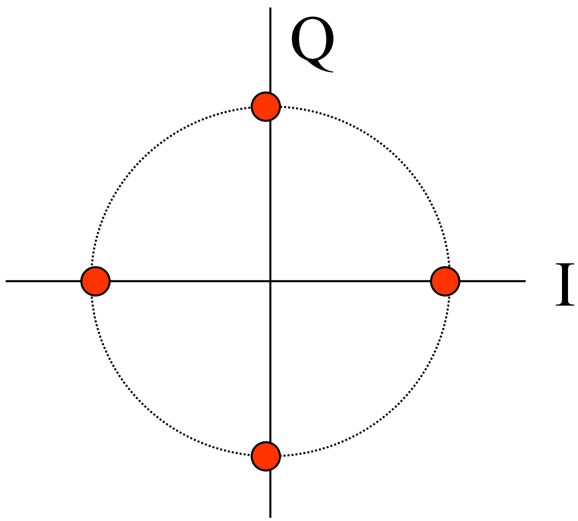
graphical representation of the complex envelope of each possible symbol state

- The x-axis represents the **in-phase** component and the y-axis the **quadrature** component of the complex envelope
- The distance between signals on a constellation diagram relates to how different the modulation waveforms are and how easily a receiver can differentiate between them.

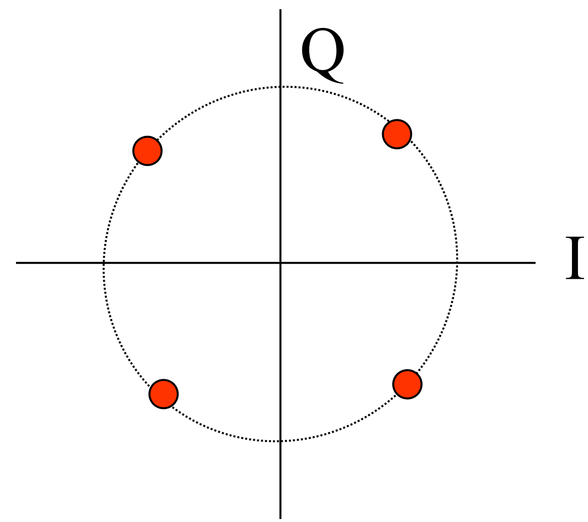
QPSK

- Quadrature Phase Shift Keying (QPSK) can be interpreted as two independent BPSK systems (one on the I-channel and one on Q), and thus the same performance but twice the bandwidth efficiency

QPSK Constellation Diagram



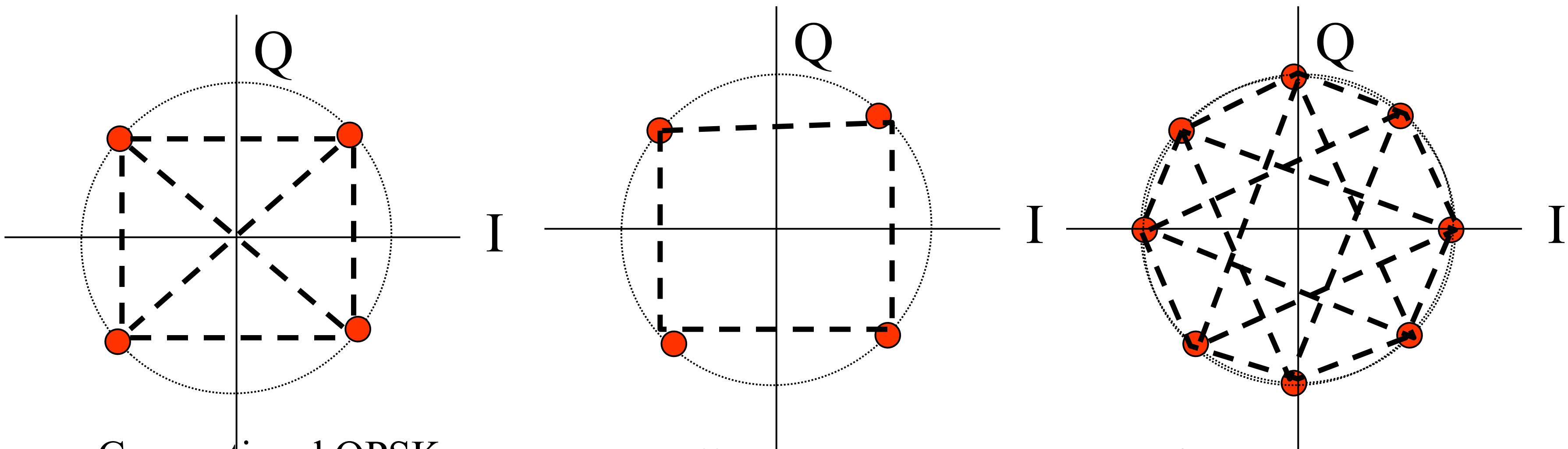
Carrier phases
{0, π/2, π, 3π/2}



Carrier phases
{π/4, 3π/4, 5π/4, 7π/4}

Quadrature Phase Shift Keying has twice the bandwidth efficiency of BPSK since 2 bits are transmitted in a single modulation symbol

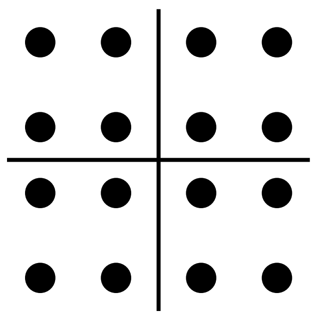
Types of QPSK



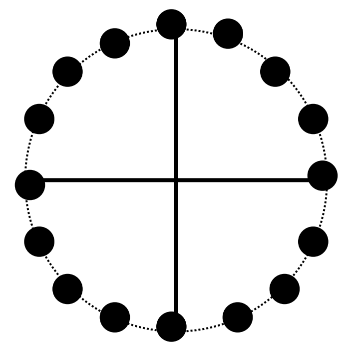
Conventional QPSK | Offset QPSK | π/4 QPSK

- Conventional QPSK has transitions through zero (i.e. 180^0 phase transition). Highly linear amplifiers required.
- In Offset QPSK, the phase transitions are limited to 90^0, the transitions on the I and Q channels are staggered.
- In π/4 QPSK the set of constellation points are toggled each symbol, so transitions through zero cannot occur. This scheme produces the lowest envelope variations.
- All QPSK schemes require linear power amplifiers

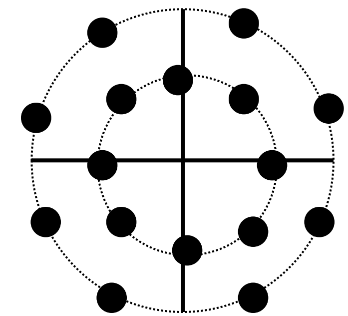
Multi-level (M-ary) Phase and Amplitude Modulation



16 QAM



16 PSK



16 APSK

- Amplitude and phase shift keying can be combined to transmit several bits per symbol.
  - Often referred to as *linear* as they require linear amplification.
  - More bandwidth-efficient, but more susceptible to noise.
- For M=4, 16QAM has the largest distance between points, but requires very linear amplification. 16PSK has less stringent linearity requirements, but has less spacing between constellation points, and is therefore more affected by noise.

Bandwidth Efficiency

$$\frac{f_b}{W} = \log_2\left(1 + \frac{E_b f_b}{\eta W}\right)$$

$f_b =$ capacity (bits per second)

$W =$ bandwidth of the modulating baseband signal (Hz)

$E_b =$ energy per bit

$\eta =$ noise power density (watts/Hz)

Thus

$E_b f_b =$ total signal power

$\eta W =$ total noise power

$\frac{f_b}{W} =$ bandwidth use efficiency

= bits per second per Hz

Comparison of Modulation Types

Modulation Format	Bandwidth efficiency C/B	Log2(C/B)	Error-free Eb/No
16 PSK	4	2	18dB
16 QAM	4	2	15dB
8 PSK	3	1.6	14.5dB
4 PSK	2	1	10dB
4 QAM	2	1	10dB
BFSK	1	0	13dB
BPSK	1	0	10.5dB

Spectral Efficiencies - Examples

- GSM Digital Cellular
  - Data Rate = 270kb/s; Bandwidth = 200kHz
  - Bandwidth efficiency = 270/200 = 1.35bits/sec/Hz
- IS North American Digital Cellular
  - Data Rate = 48kb/s; Bandwidth = 30kHz
  - Bandwidth efficiency = 48/30 = 1.6bits/sec/Hz

Stop ! Next....?

Modulation Summary

- Phase Shift Keying (PSK) is often used as it provides efficient use of RF spectrum. $\pi/4$ QPSK (Quadrature PSK) reduces the envelope variation of the signal.
- High level M-array schemes (such as 64-QAM) are very bandwidth-efficient but more susceptible to noise and require linear amplification
- Constant envelope schemes (such as GMSK) allow for non-linear power-efficient amplifiers
- Coherent reception provides better performance but requires a more complex receiver

References

- Campbell AT. *Untangling the Wireless Web – Radio Channel Issues*, Lecture Notes E6951, comet.columbia.edu/~campbell
- Fitton M. *Principles of Digital Modulation*, Lecture Notes ICTP 2002
- Proakis J. *Digital Communications,* McGraw & Hill Int.
- Rappaport TS. *Wireless Communications,* Prentice Hall PTR

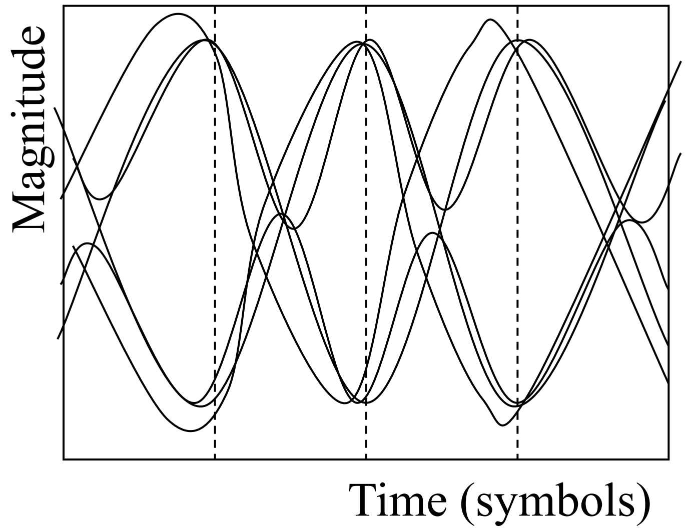
Ultra-Wideband (UWB) Systems

- Radio or wireless devices where :

the occupied bandwidth > 25% of the center frequency [1.5 GHz]

- Radio or wireless systems that **use narrow pulses** (on the order of 1 to 10 nanoseconds), also called carrierless or impulse systems, for communications and sensing (short-range radar).
- Radio or wireless systems that **use time-domain modulation methods** (*e.g.*, pulse-position modulation) for communications applications, or time-domain processing for sensing applications.

Eye Diagram

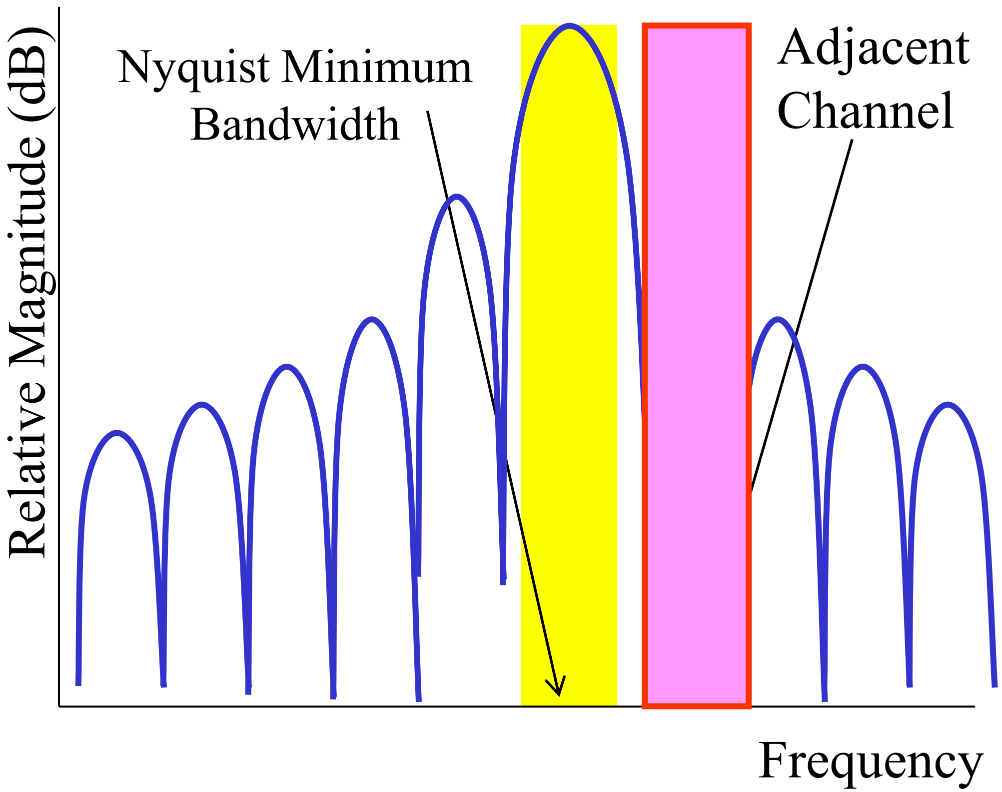


- Eye pattern is an oscilloscope display in which digital data signal from a receiver is repetitively superimposed on itself many times (sampled and applied to the vertical input, while the data rate is used to trigger the horizontal sweep).
- It is so called because the pattern looks like a series of eyes between a pair of rails.
- If the “eye” is not open at the sample point, errors will occur due to signal corruption.

GMSK

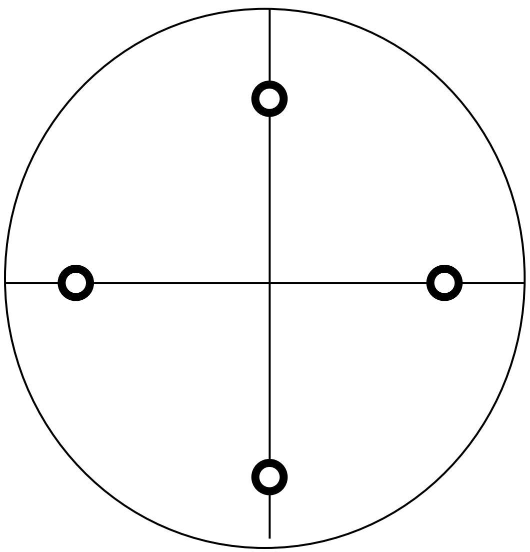
- Gaussian Minimum Shift Keying (GMSK) is a form of continuous-phase FSK in which the phase change is changed between symbols to provide a constant envelope. Consequently it is a popular alternative to QPSK
- The RF bandwidth is controlled by the Gaussian low-pass filter bandwidth. The degree of filtering is expressed by multiplying the filter 3dB bandwidth (B) by the bit period of the transmission (T), i.e. by BT
- GMSK allows efficient class C non-linear amplifiers to be used

Modulation Spectra

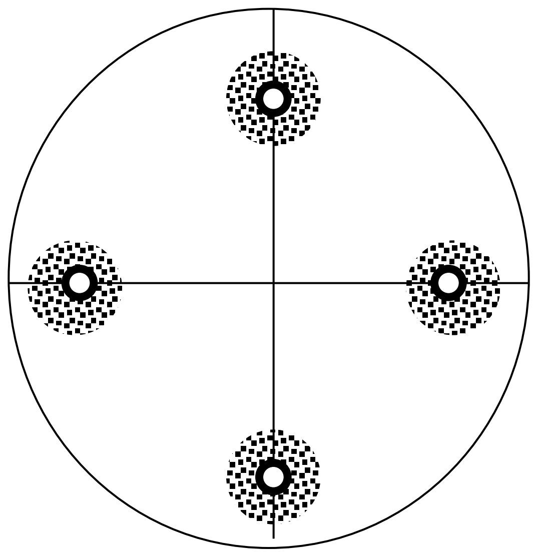


- The Nyquist bandwidth is the minimum bandwidth that can represent a signal (within an acceptable error)
- The spectrum occupied by a signal should be as close as practicable to that minimum, otherwise adjacent channel interference occur
- The spectrum occupied by a signal can be reduced by application of filters

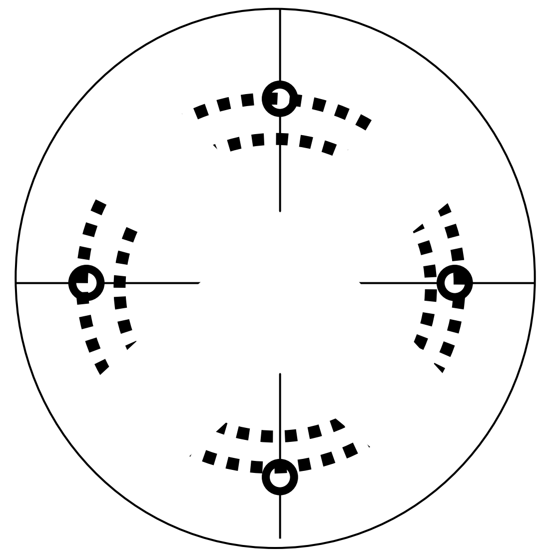
Distortions



Perfect channel



White noise



Phase jitter