RF Fundamentals Seminar

Part 5: Digital Modulation

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Make ideas real

Agenda – Digital Modulation

- Modulation
- Polar Display (I & Q)
- IQ Modulation
- Types of Digital Modulation
- Filtering and Inter-Symbol Interference

What is Modulation?
Transmitting Information

Modulate:
Modify some characteristic of a carrier

Demodulate:
Detect the modifications

Any reliably detectable change in signal characteristics can carry information

$$V(t) = A \sin(2\pi ft + \phi)$$

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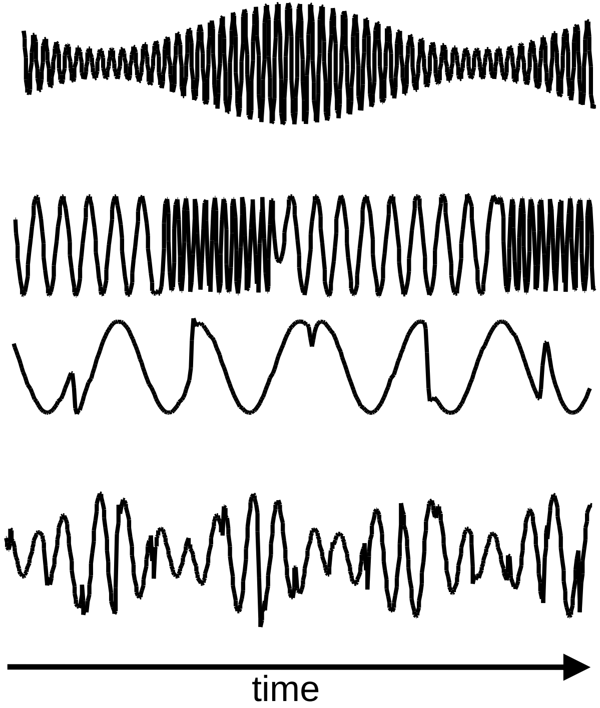
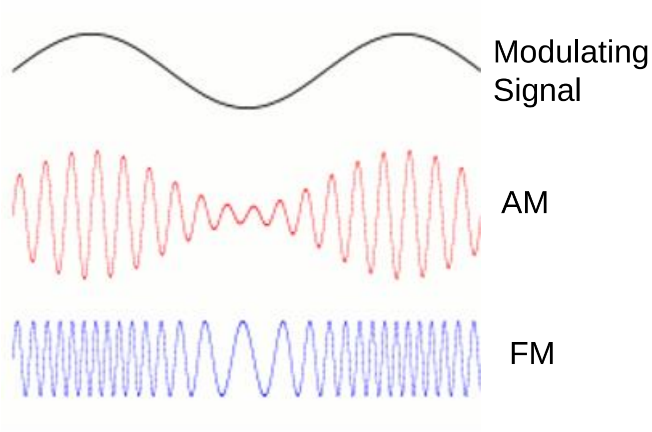
What is Modulation?
Signal Characteristics to Modify

Amplitude

Frequency
or
Phase

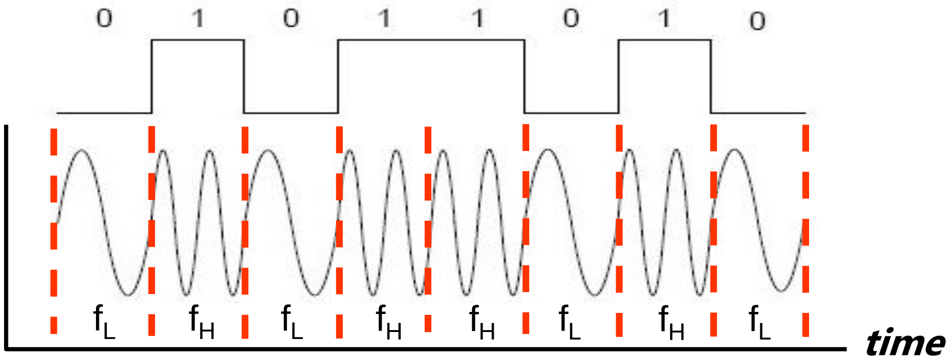
Amplitude
and Phase





Simple Digital Modulation: FSK (Frequency Shift Keying)

- Same as analog FM, but with discrete levels, not analog voice or music, as the modulating signal
- Frequency shifts between f_H and f_L (2FSK)
- Shifts between 4 frequencies in 4FSK
- MSK: Minimum Shift Keying
  - Special Case of FSK where f_Δ= bit rate/4
  - Occupies minimum spectrum for given bit rate
  - Used in GSM (SR: 270.8333 kSym/s, f_Δ= 67.708 kHz, Gaussian filtered: GMSK)

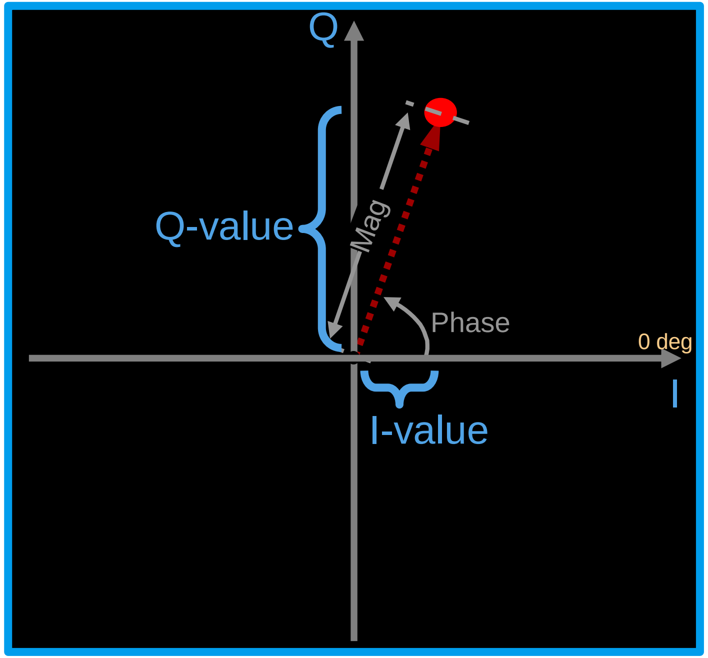


$f_L = f_c - f_\Delta$

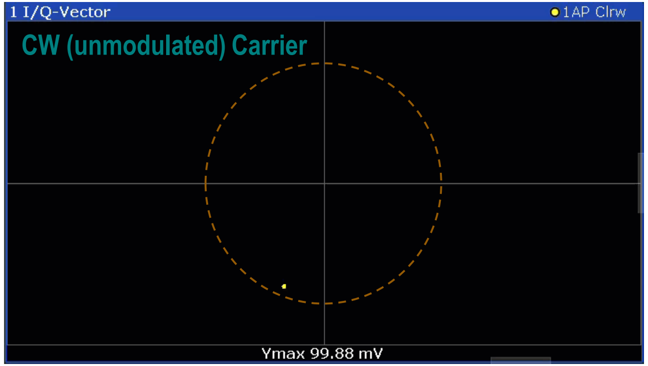
$f_H = f_c + f_\Delta$

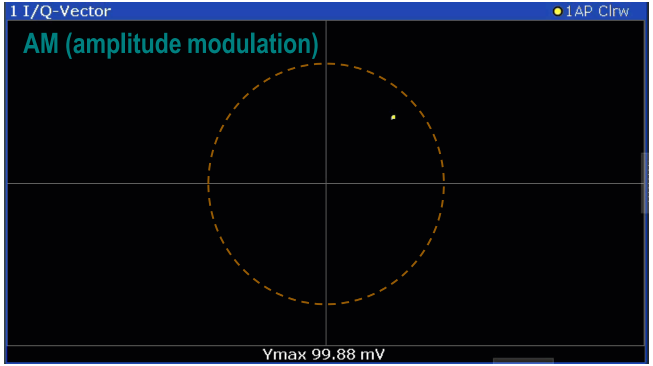
Polar Display

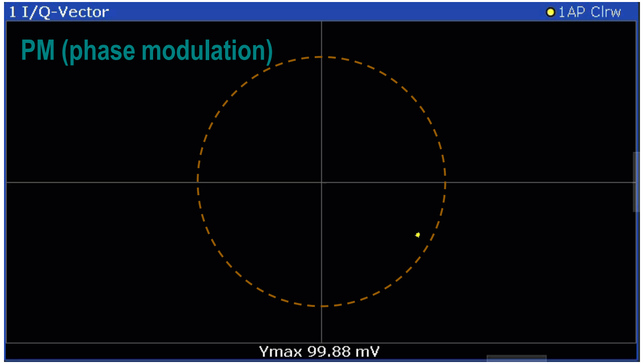
- Every point on display represents a specific magnitude and phase (phasor diagram)
- Magnitude is the distance from center of the plot and indicates linear voltage
- Phase is relative to a reference local oscillator or clock
- Converting Mag and Phase to rectangular (Cartesian) coordinates results in I and Q values

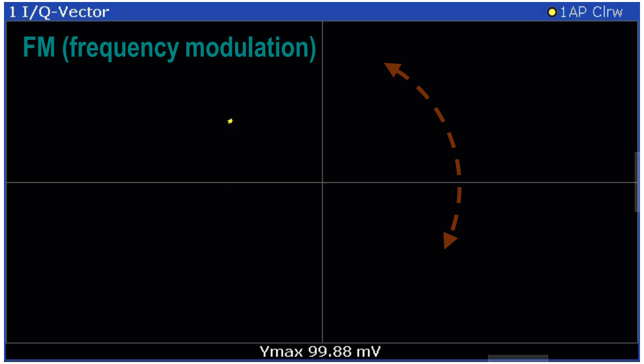


Analog Modulation on Polar Display



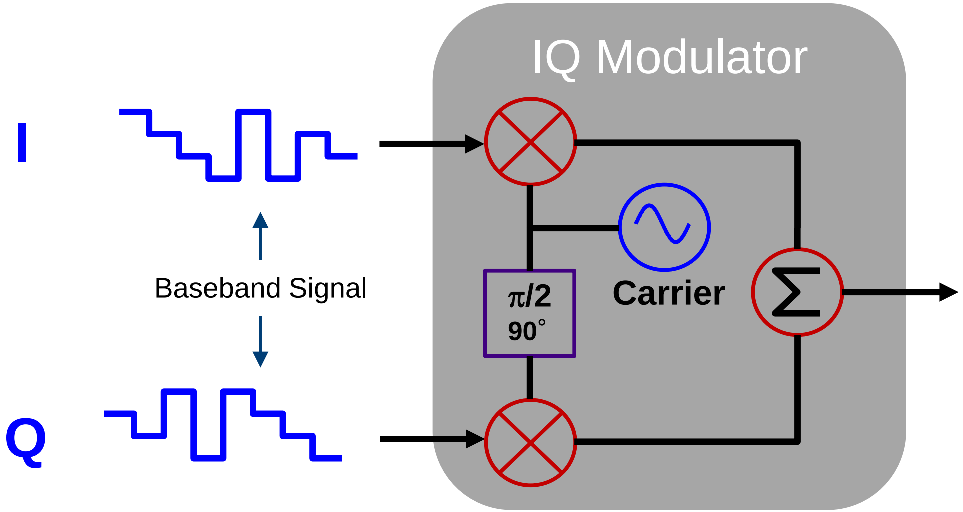






IQ Modulator

- Easier to build than a ‘Magnitude/Phase’ modulator
- Enables simultaneous amplitude and phase modulation using I and Q inputs
- Modulating signal can be treated as a phasor represented with it’s I and Q components
- IQ modulator can be used for digital or analog modulation (or any arbitrary signal)



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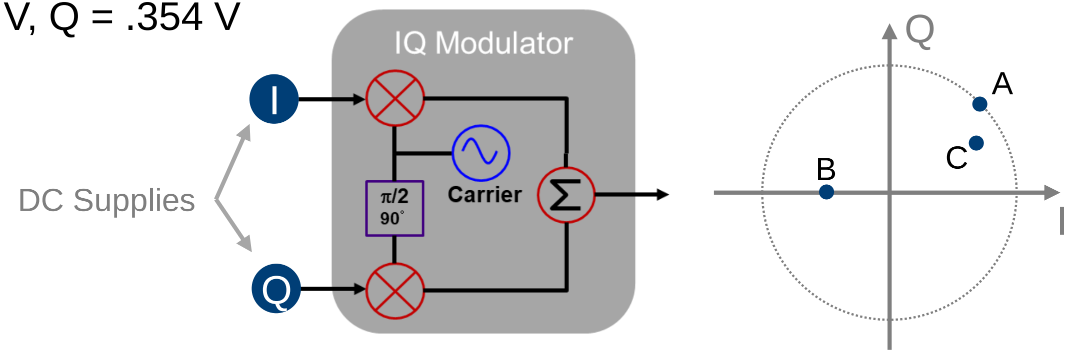
IQ Modulation – CW Demonstration

- We can use an IQ modulator to create a CW signal with a specific amplitude (A) and phase (ϕ)
  - $I = A\cos(\phi)$
  - $Q = A\sin(\phi)$

- Examples (assuming 1 V max input to modulator so 'A' ranges from -1 to +1 V):
  A. 0 dB (A=1) at 45º: I = 0.707 V, Q = 0.707 V
  B. -6 dB (A=0.5) at 180º: I = -0.5 V, Q = 0 V
  C. -3 dB (A=.707) at 30º: I = 0.612 V, Q = .354 V



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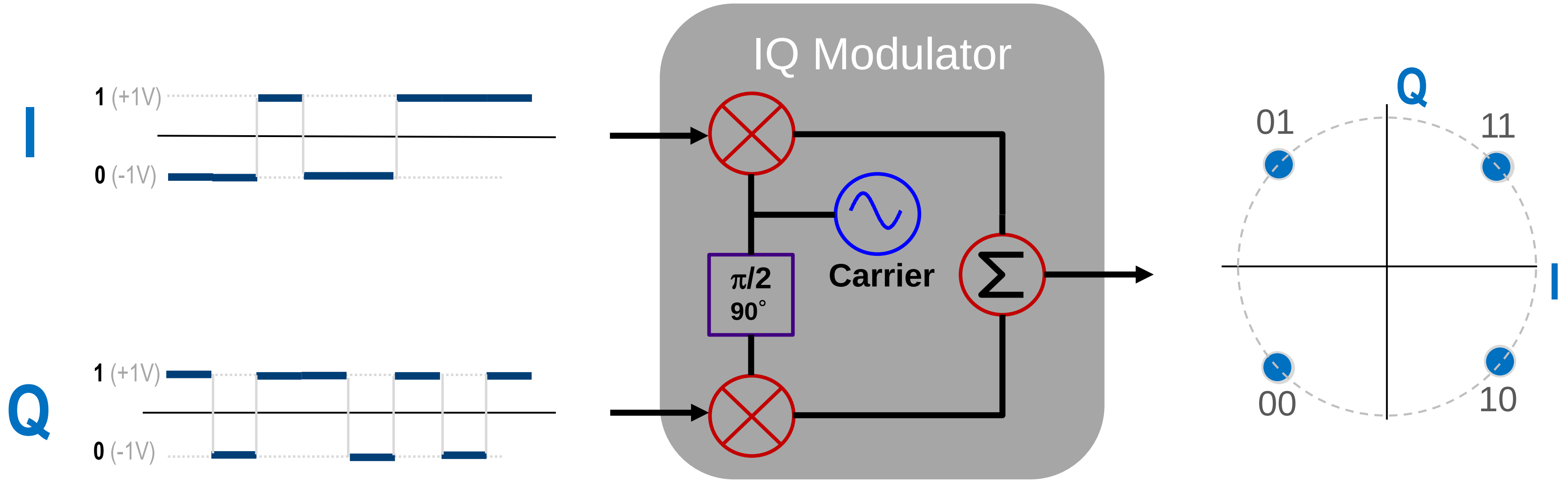
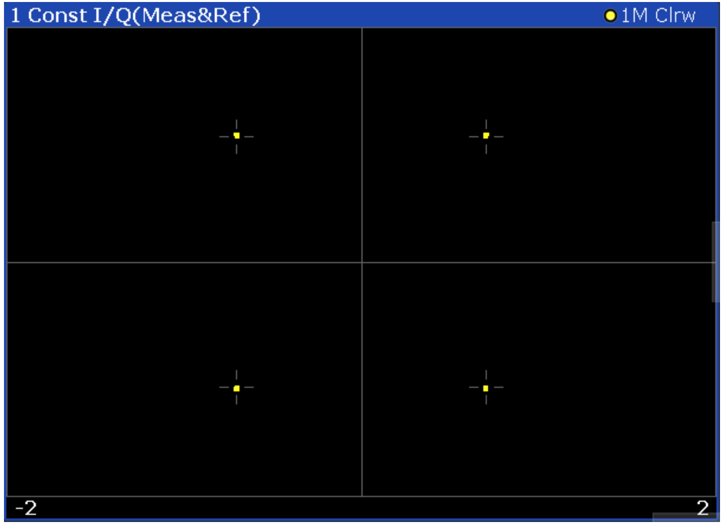
Modulating Digital Data onto a Carrier

- We want to transmit the following hex data bytes: 4 D 3 B
- In binary this is: 0100 1101 0011 1011
- We route the first bit to 'I' and the second bit to 'Q', then repeat with next bits

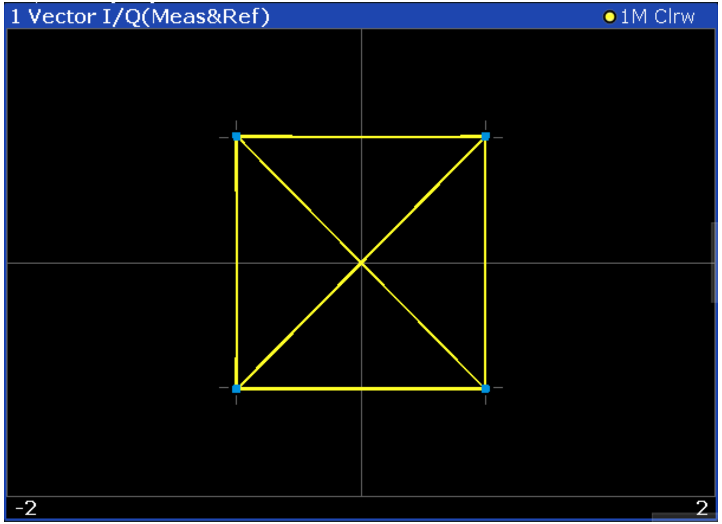


Constellation Diagrams vs. Vector Diagrams

- Constellation Diagrams show the signal location in the IQ domain at the symbol clock times
- Vector Diagrams additionally show the signal location in the IQ domain between clock times

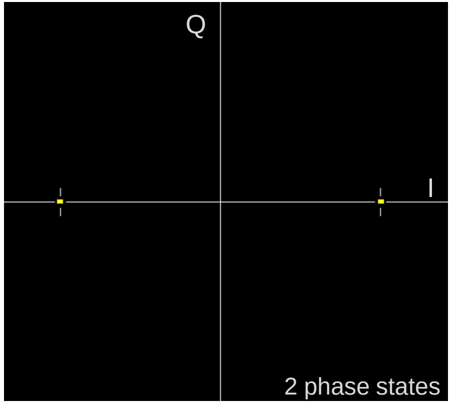


Constellation Diagram
(IQ location at symbol clock times)

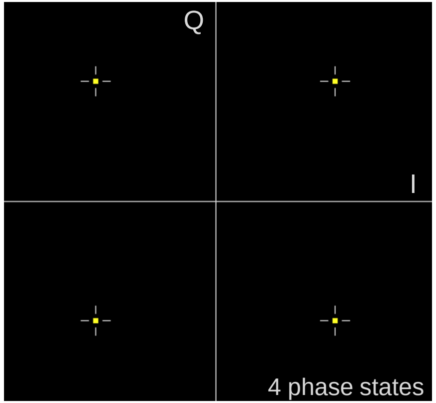


Vector Diagram
(IQ location at symbol clock and during transitions)

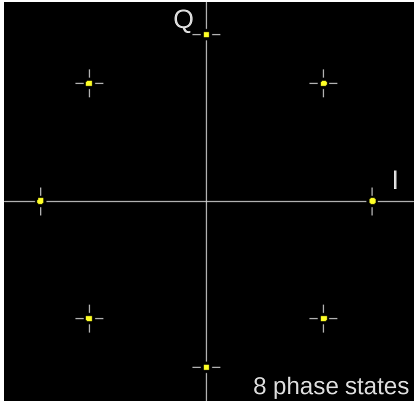
Digital Phase Modulation: Phase Shift Keying (PSK)



BPSK
(Binary Phase Shift Keying)



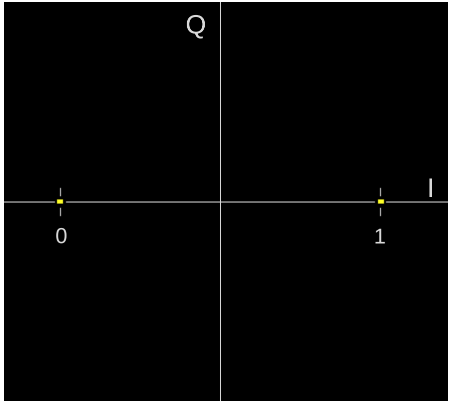
QPSK
(Quadrature Phase Shift Keying)



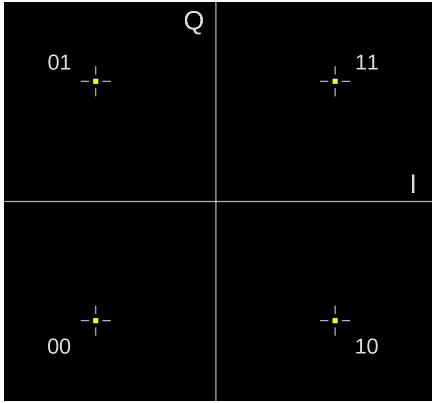
8PSK
(8 State Phase Shift Keying)

Constellation Diagrams

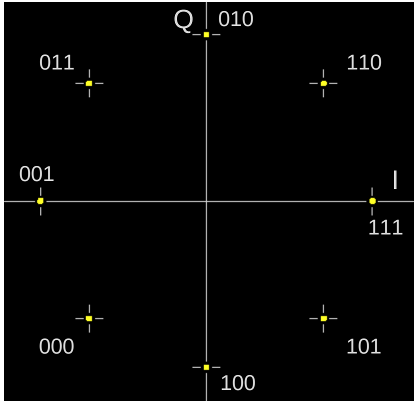
Bit Rate vs. Symbol Rate



BPSK
(1 bit/symbol)



QPSK
(2 bits/symbol)



8PSK
(3 bits/symbol)

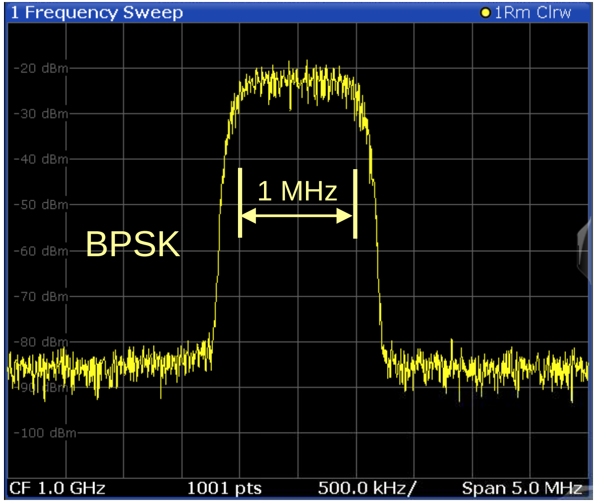
Bit Rate: frequency of the system bit stream

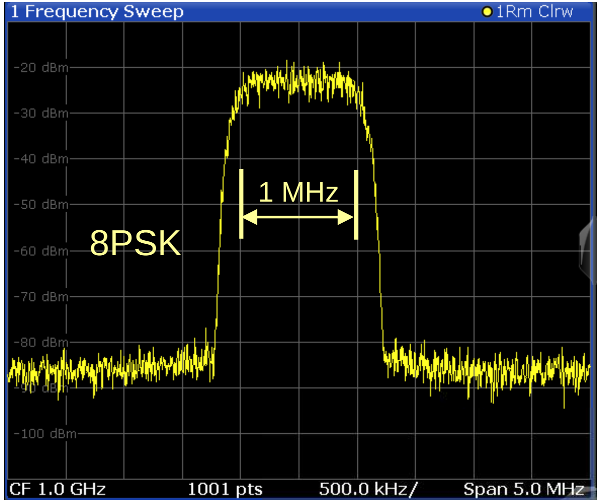
Symbol Rate: bit rate divided by bits per symbol (also called Baud Rate*)

*named for Émile Baudot – telecommunications pioneer

Spectral Bandwidth, Bit Rate, and Symbol Rate

► Signal Bandwidth depends on symbol rate, not bit rate





BPSK: 1 bit / symbol
1 Msps = **1 Mbps**

8PSK: 3 bits / symbol
1 Msps = **3 Mbps**

Higher order modulation formats transmit higher bit rate in same bandwidth

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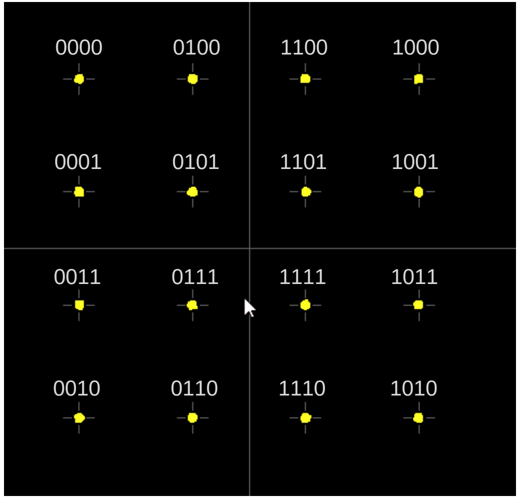
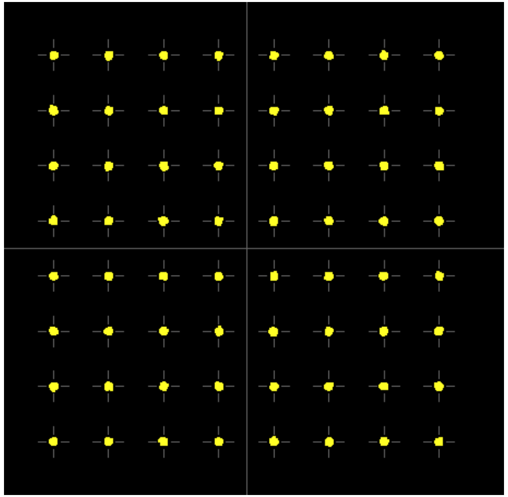
Quadrature Amplitude Modulation (QAM)

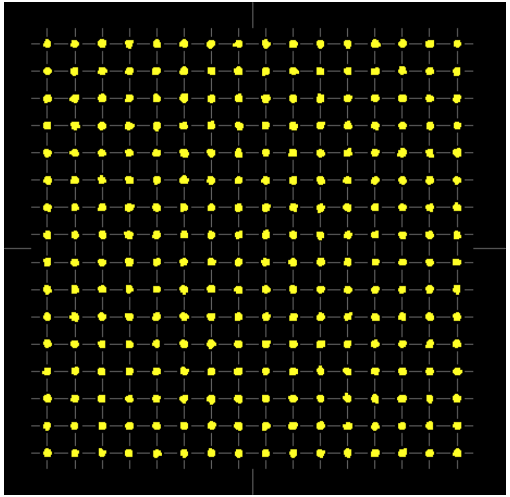
- Other QAM Orders: 32, 128, 512, 1024, 2048, 4096, 8192, 16384
- QPSK is sometimes called 4QAM



16QAM
(4 bits per symbol)



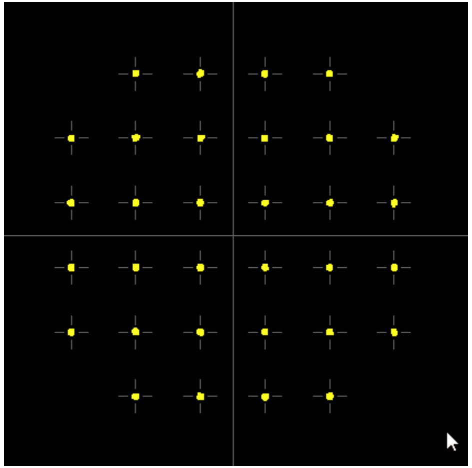
64QAM
(6 bits per symbol)



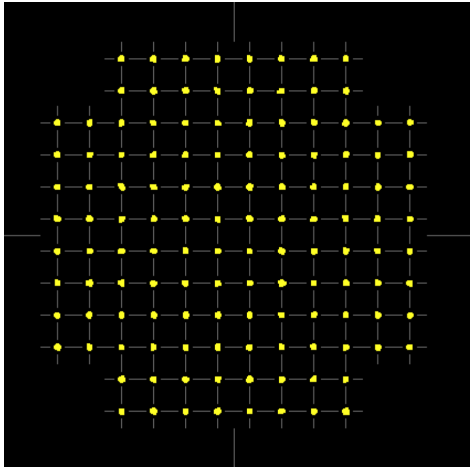
256QAM
(8 bits per symbol)

Odd-Order QAM

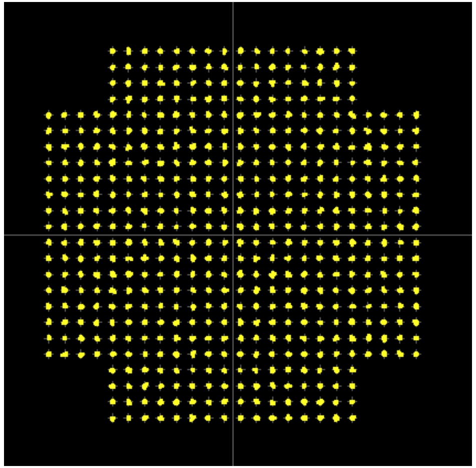
- Standard QAM has orders that are powers of 2 <u>and</u> perfect squares: 16, 64, 256, 1024, 4096, etc.
- Odd-order QAM has orders that are power of 2 and not perfect squares: 32, 128, 512, 2048, etc.
- Symbols are removed from the square to force the number of symbols to be a power of 2
- Corner symbols are removed since they take the highest power to transmit



32QAM
(5 bits per symbol)



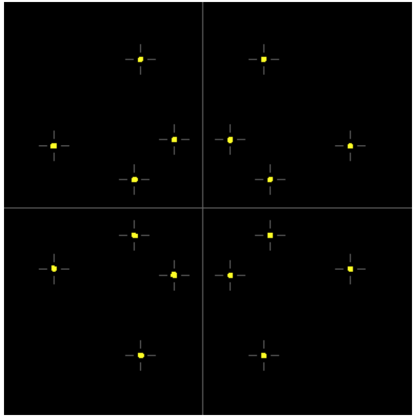
128QAM
(7 bits per symbol)



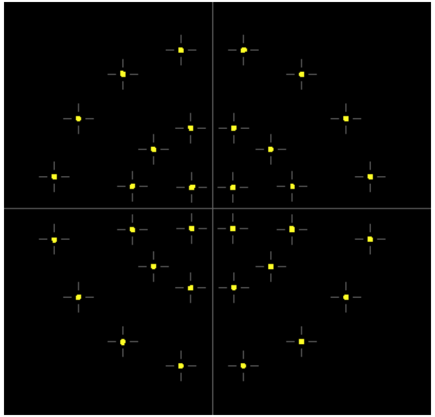
512QAM
(9 bits per symbol)

APSK Modulation (Amplitude Phase Shift Keying)

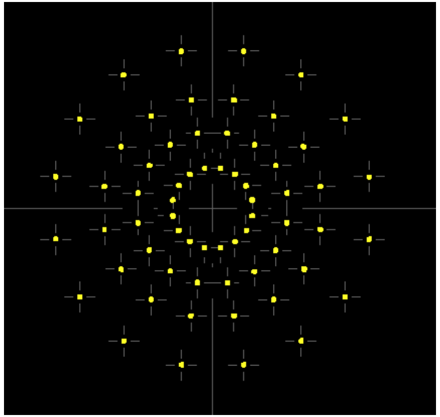
- Constellation symbols are arranged in concentric rings
- Robust against compression and AM/PM conversion
- Commonly used in satellite communications



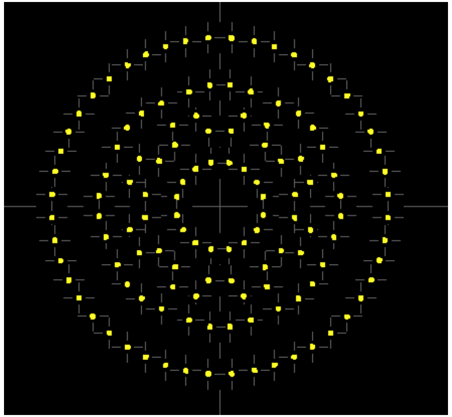
16APSK



32APSK



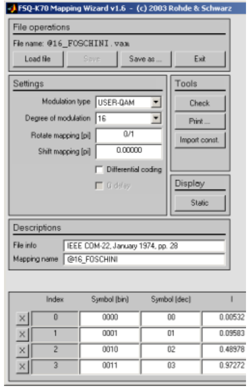
64APSK

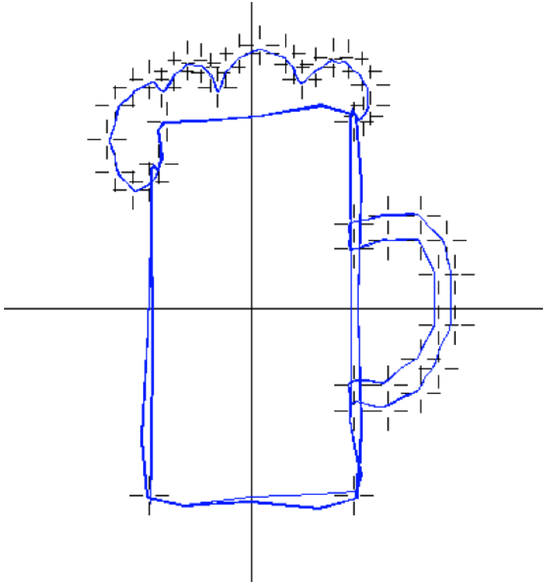


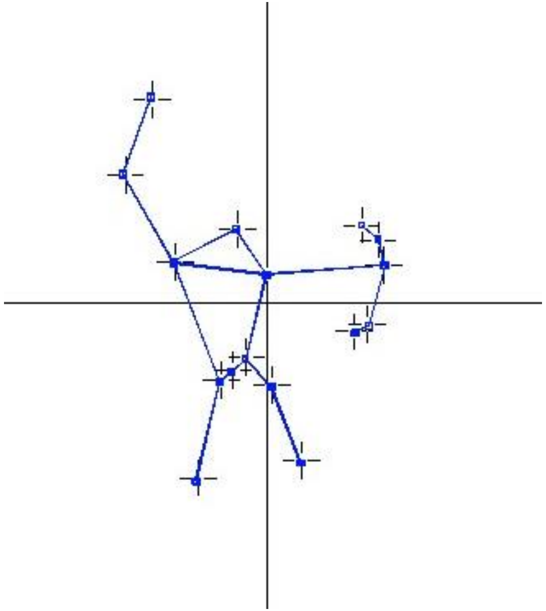
128APSK

Constellations can be Arbitrary!

R&S Mapping Wizard







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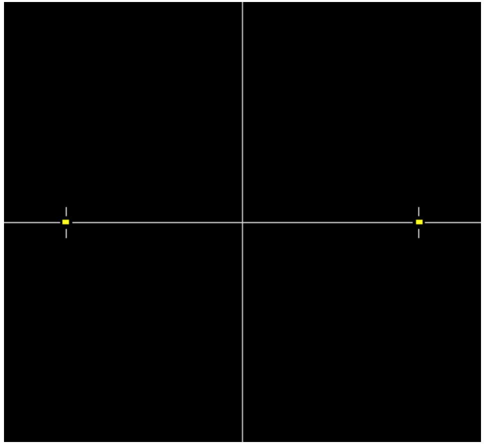
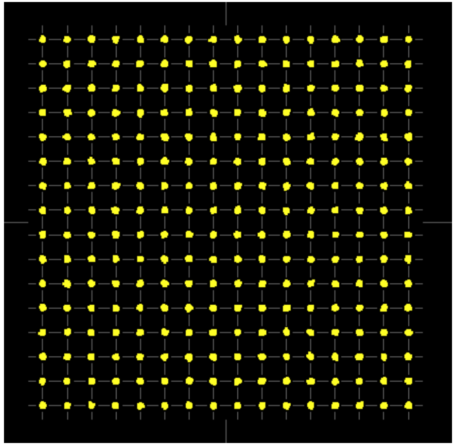
High Order vs. Low Order Modulation

- All digital modulations occupy the same bandwidth when transmitted at the same symbol rate
- Question: Why would we use BPSK when 256QAM gives us 8x the bit rate?
- Answer: Noise



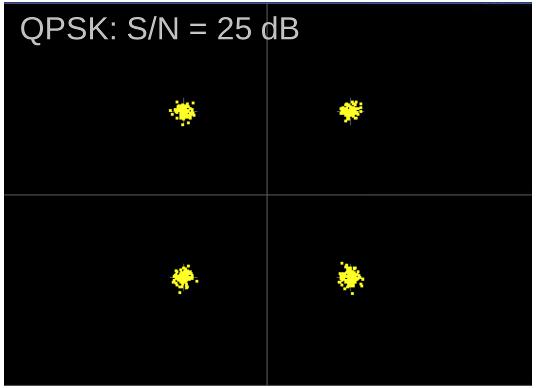
BPSK
(1 bit per symbol)

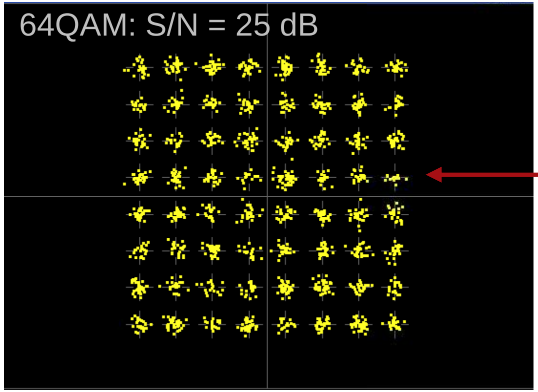


256QAM
(8 bits per symbol)

Modulation Format and Noise

- Noise deviates signal from ideal symbol targets and causes symbol errors if adjacent symbol targets are close
- The dense constellations of higher complexity formats makes them more susceptible to noise
- Shannon-Hartley Theorem gives the maximum data rate (bit rate) in the presence of noise
  - $C = B * \log_2(1 + S/N_{lin})$
    where C is channel capacity in bits/s, B is channel bandwidth, S/N is signal to noise ratio (linear)
  - For high S/N (>15 to 20dB) this simplifies to $C = 0.332 * B * S/N_{dB}$

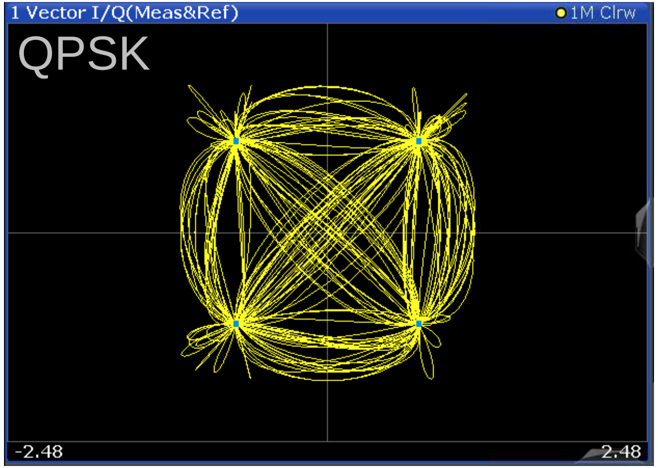


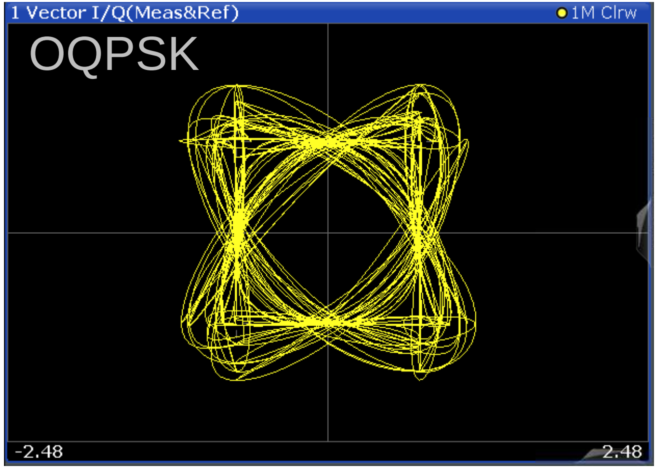


Higher probability of symbol (bit) error with same S/N ratio

Reducing Peak / Avg Ratio (Crest Factor)

- OQPSK (Offset QPSK)
  - I and Q baseband signals are offset from each other by ½ symbol
  - I changes then Q changes then I changes, etc.
  - I and Q don't transition at the same time so the center is avoided (reduces pk/avg ratio)
  - Lower cost, less linear amplifiers can be used





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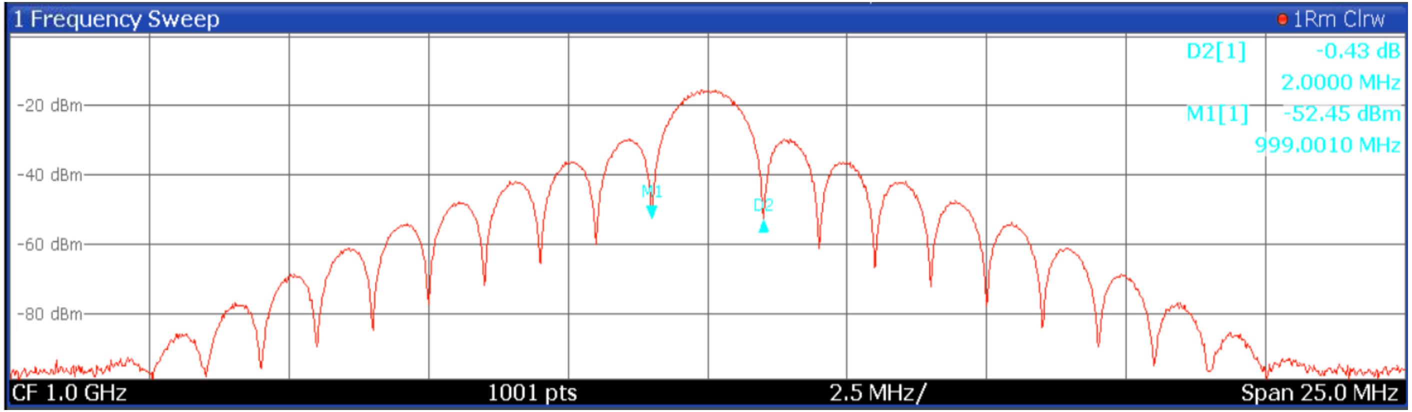
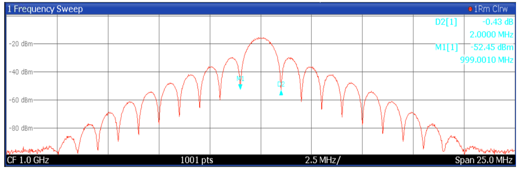
Spectrum of Unfiltered 16QAM Signal (Fast I/Q Transitions)

► How can we limit the occupied bandwidth of this signal?

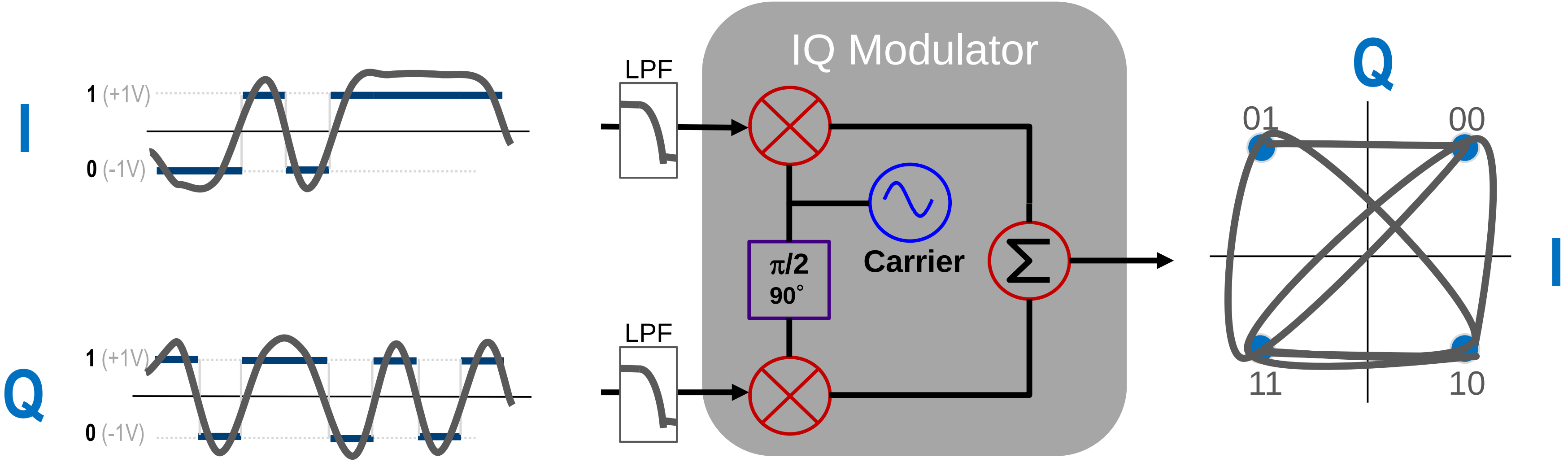


1 Msym/s

Filtering



- Remember our IQ Modulator and data stream
- Abrupt changes in time domain cause spectral splattering in frequency domain
- To avoid this use low-pass filtering on the baseband signal to smooth the transitions which reduces the bandwidth in the frequency domain



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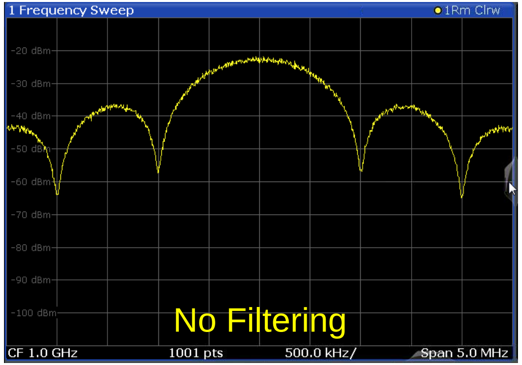
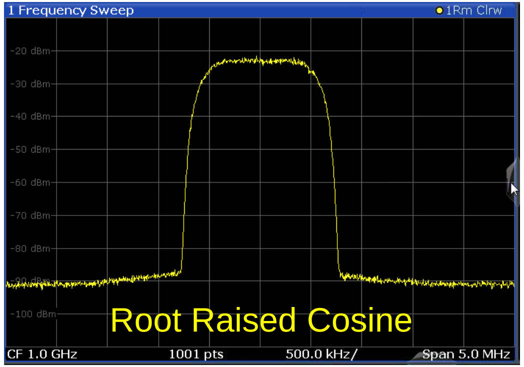
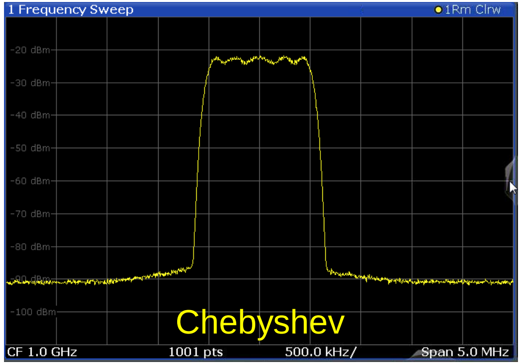
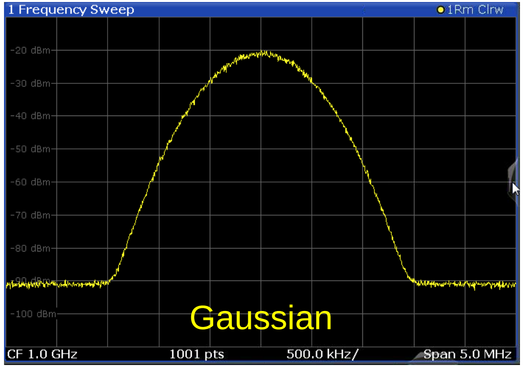
Spectrum with some Common Filter Types
QPSK 1 Msps

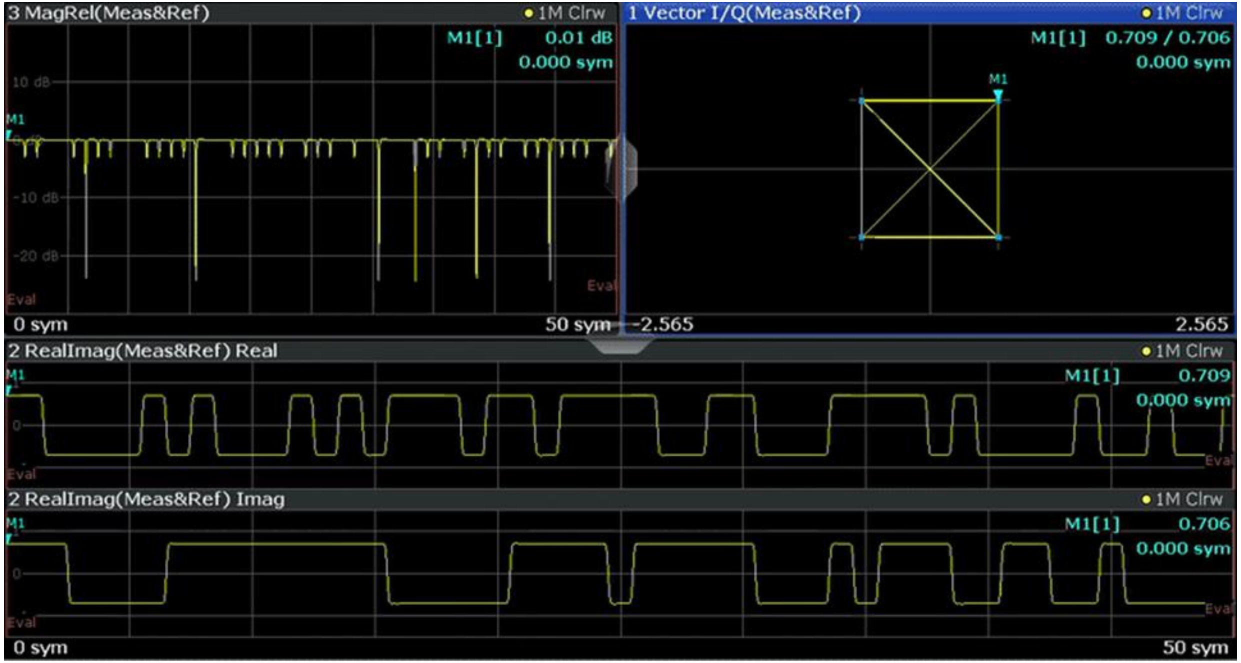








QPSK signal with no filtering



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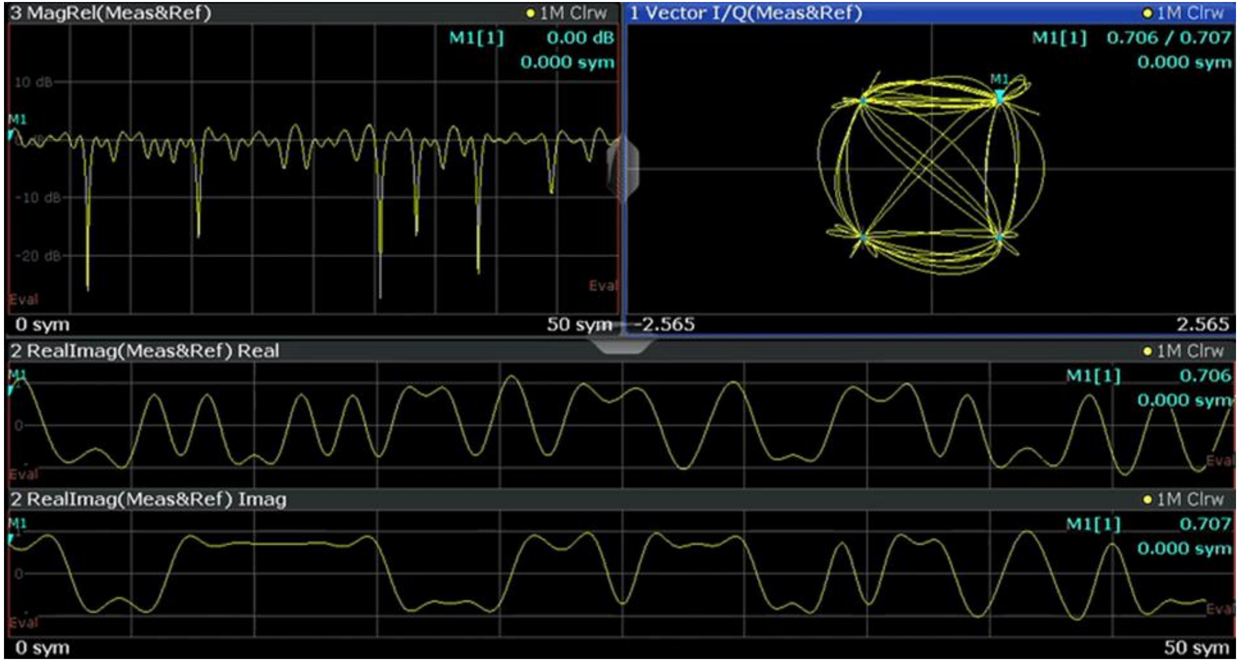
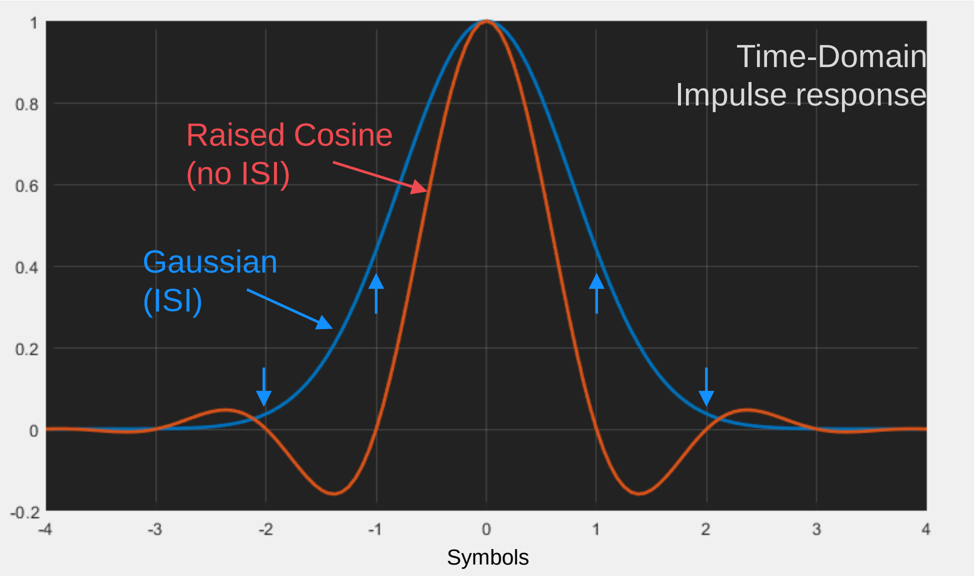
QPSK signal with RRC filtering



Inter-Symbol Interference (ISI)

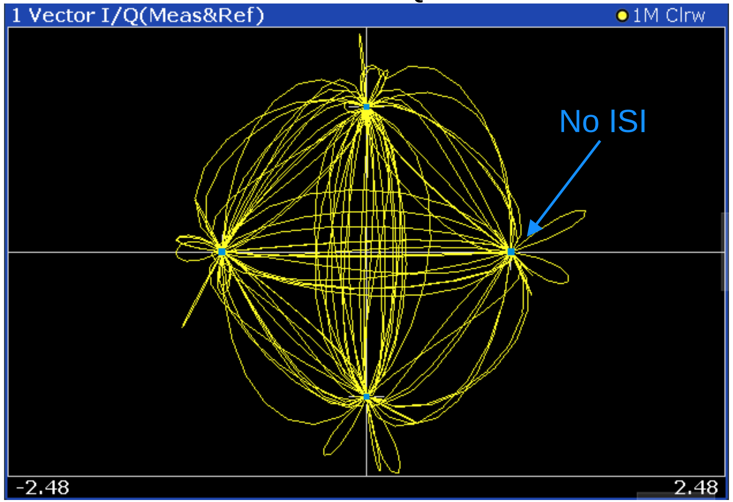
- If the time-domain impulse response of the filter is non-zero at adjacent symbols, ISI occurs
- A filter with ISI causes the IQ position of the signal to be dependent on previous and subsequent symbols
- ISI-free filters are called “Nyquist” filters – Raised Cosine (RC) is an example of an ISI-free filter



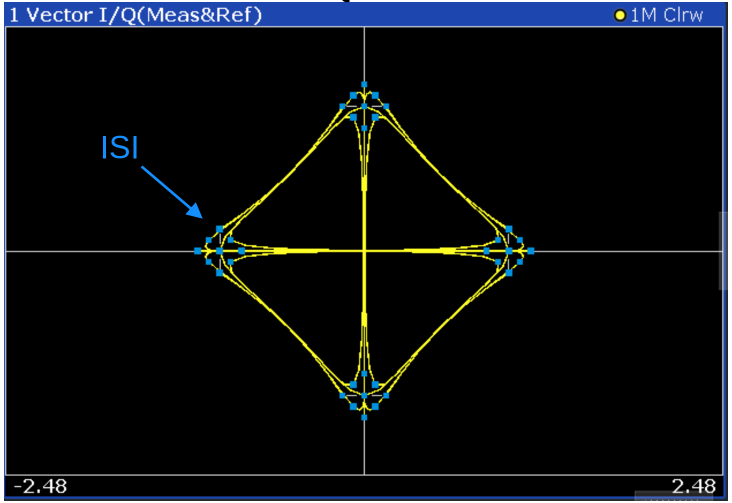
Inter-Symbol Interference (ISI)

- ISI is obvious in the Vector Diagram (blue markers show signal at symbol clock time)
- Raised Cosine filters are commonly used in single-carrier communication systems with high-order modulation schemes
- Gaussian filters are generally used with constant envelope modulation such as FSK and MSK

Raised Cosine filtered QPSK with no ISI



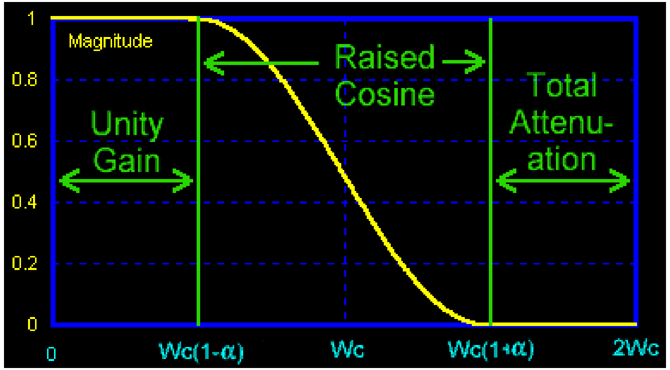
Gaussian filtered QPSK with obvious ISI



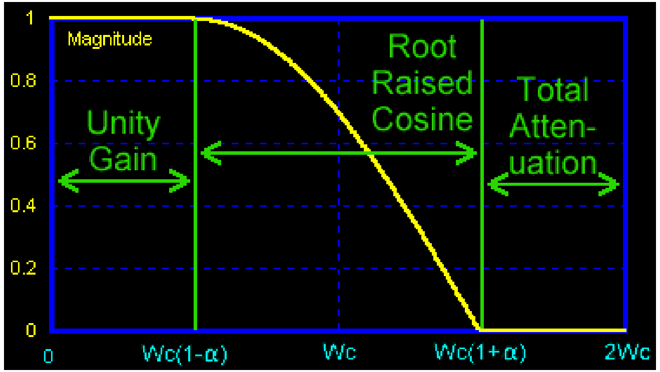
Digital Modulation: RC and RRC Filters

- RC (raised cosine) and RRC (root raised cosine) are very common
- RC filters have zero ISI (inter-symbol interference)
- The “alpha” parameter determines the sharpness of the filter and is generally between 0.1 and 1

RC – Raised Cosine



RRC – Root Raised Cosine



Frequency response

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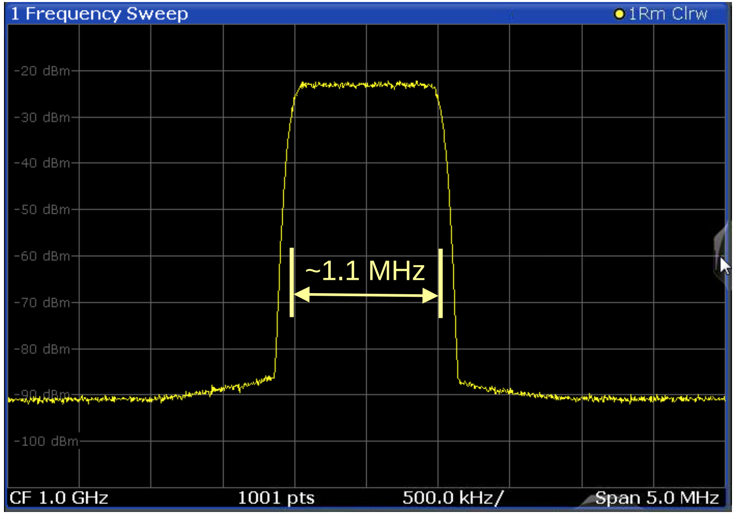
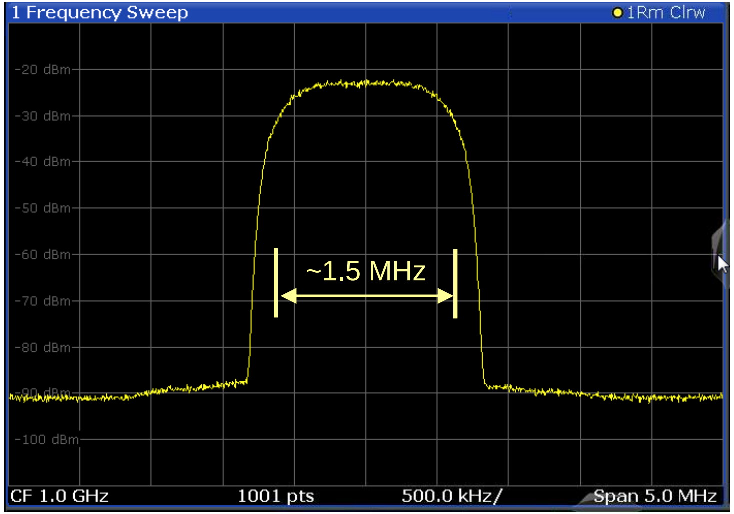
RRC Filter Alpha: Effect on Bandwidth



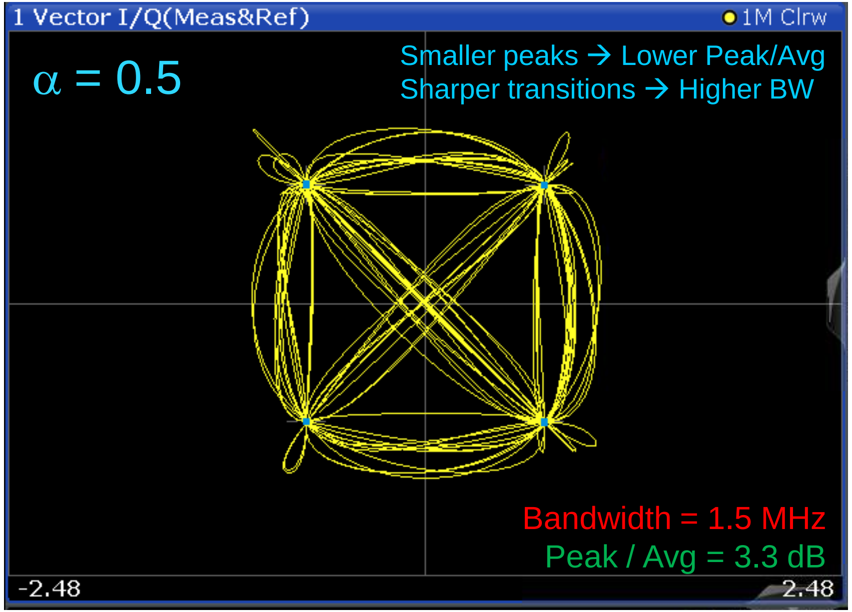
1Msps, RRC, α = .1

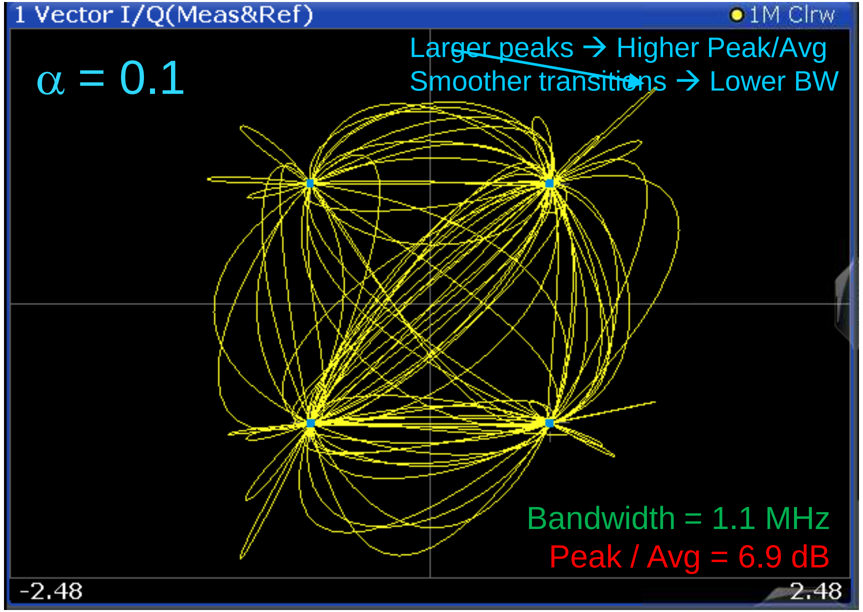


1Msps, RRC, α = .5

Signal BW $\cong$ Symbol Rate * $(1 + \alpha)$

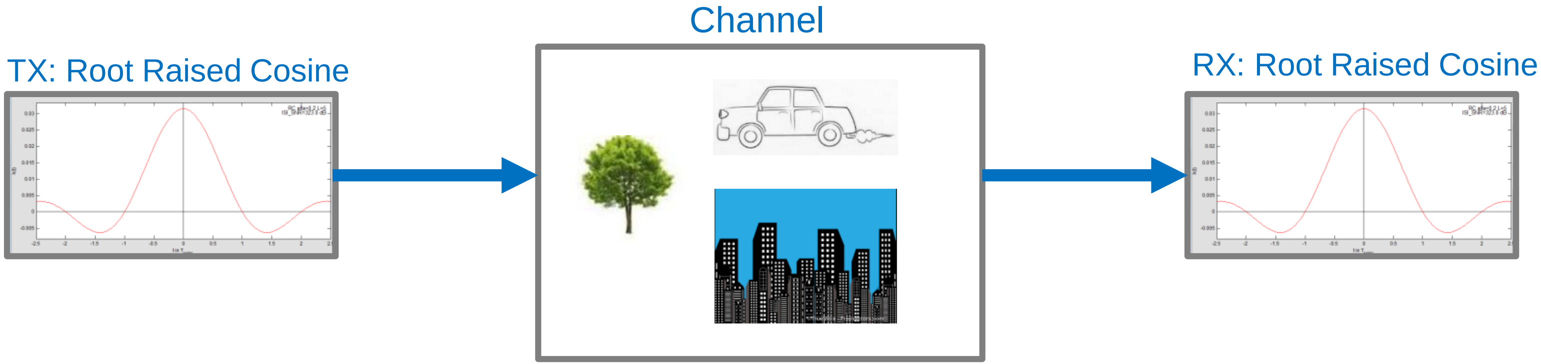
RRC Filter Alpha: Effect on Peak/Avg Ratio





Why Use ‘Root’ Raised Cosine Filters?

- Three things we would like to have:
  - We want a filter at the transmitter to limit transmitted bandwidth
  - We want a filter at the receiver to reduce noise added by the channel
  - We want to use a Raised Cosine (RC) filter in our system due to it’s benefits
- Two Root Raised Cosine (RRC) responses cascaded → Raised Cosine



Digital Modulation: Summary

- Digital modulation is really a special case of analog modulation (modifying amplitude and phase)
- The I/Q plane is another way of representing the amplitude and phase of a signal
- Signal bandwidth is a function of Symbol Rate, not Bit Rate (and filter characteristics)
- Bit rate is limited by transmit power and signal to noise ratio (Shannon-Hartley Theorem)
- Filtering is used to limit bandwidth of transmitted signal
- Some filter types introduce ISI (inter-symbol interference)
- Filter type is a tradeoff between occupied bandwidth, crest factor, and ISI