RF Fundamentals Seminar
Part 5: Digital Modulation and Vector Signal Analysis

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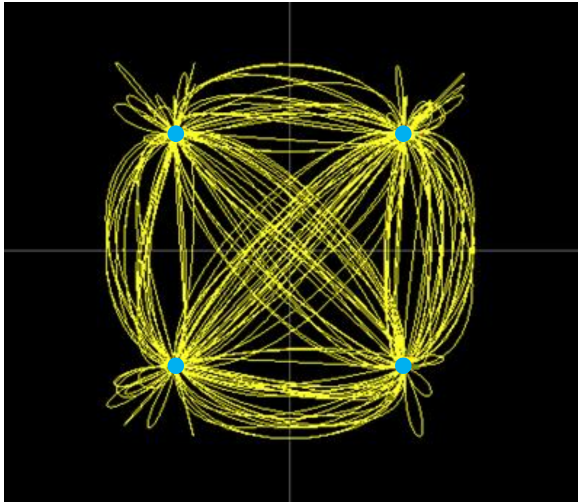
Make ideas real

Questions to be answered…

- What does ‘Digital Modulation’ mean?
- What is ‘IQ’ and why do we use it?
- What is this diagram called? What does it show?
- What is the significance of the blue dots?
- What is that crazy curve that connect the dots?
- What determines the shape of the curve?
- How many types of digital modulation are there?
- How do bit rate, symbol rate, and Baud rate relate?
- How does filtering work?
- What do PSK, QAM, APSK, RRC, ISI, and EVM mean?



Agenda – Digital Modulation

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

What is Modulation?
Transmitting Information

Modulate:
Modify some characteristic of a carrier

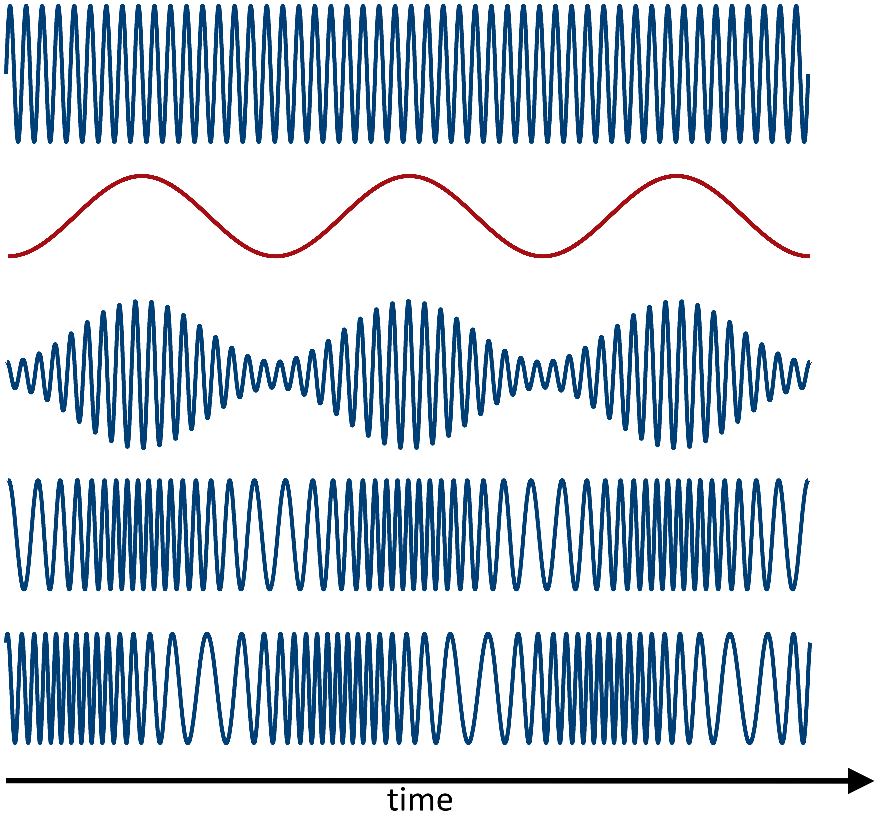
Demodulate:
Detect the modifications

Any reliably detectable change in signal characteristics can carry information

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

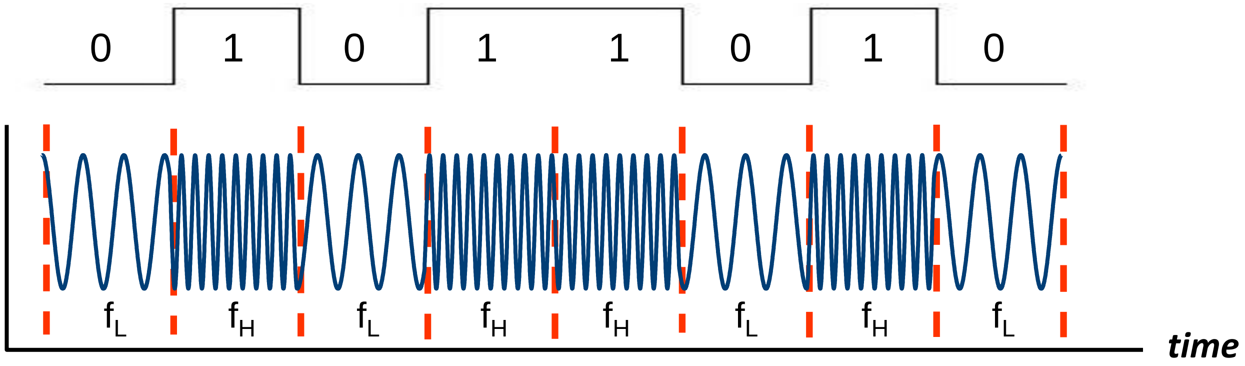
Modulation: Signal Characteristics to Modify

CW Carrier Wave		$V(t) = A \sin(2\pi f_c t + \phi)$
Modulating Wave		
Amplitude (AM)		$V(t) = A(t) \sin(2\pi f_c t + \phi)$
Frequency (FM)		$V(t) = A \sin(2\pi f(t) t + \phi)$
Phase (PM or ϕM)		$V(t) = A \sin(2\pi f_c t + \phi(t))$



Simple Digital Modulation: FSK (Frequency Shift Keying)

- Same as analog FM, but with discrete levels as the modulating signal (not analog voice or music)
- Frequency shifts between f_H and f_L (2 FSK)
- Shifts between 4 frequencies in 4 FSK
- 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)

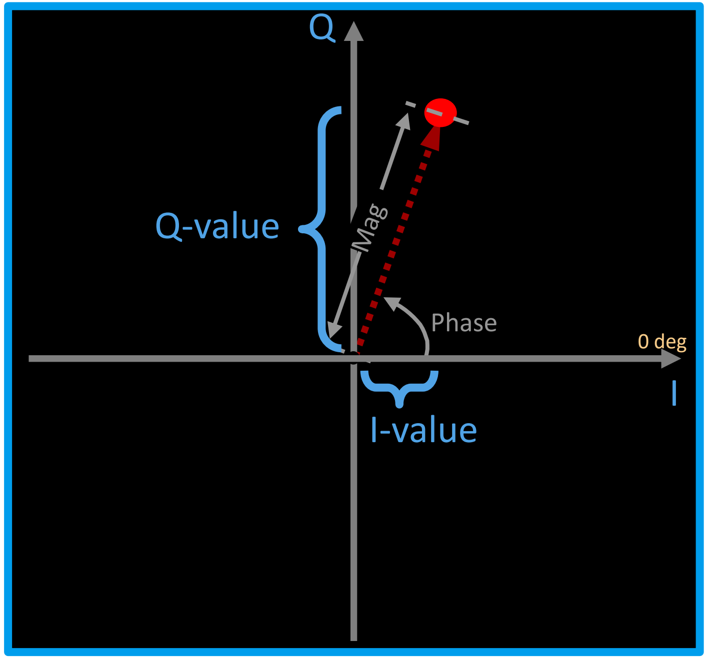


$f_L = f_c - f_\Delta$

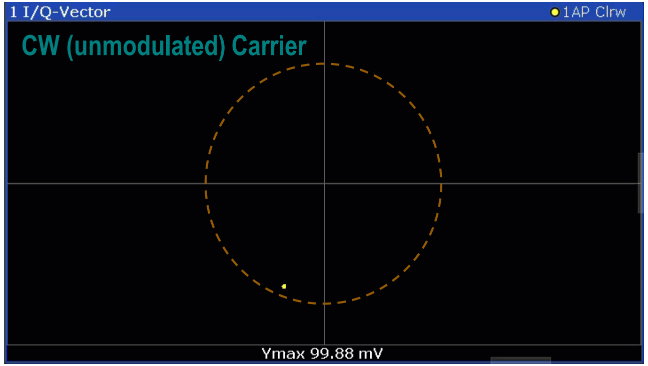
$f_H = f_c + f_\Delta$

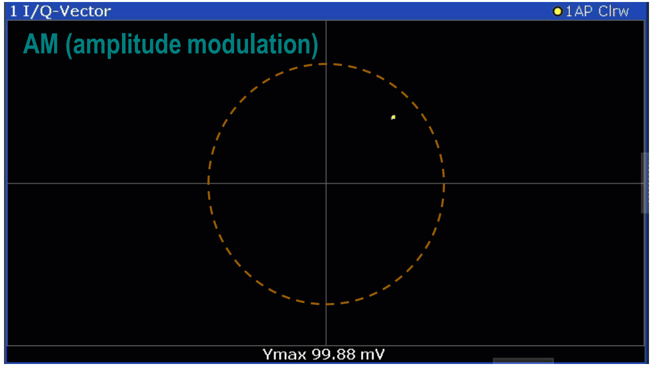
Polar Display

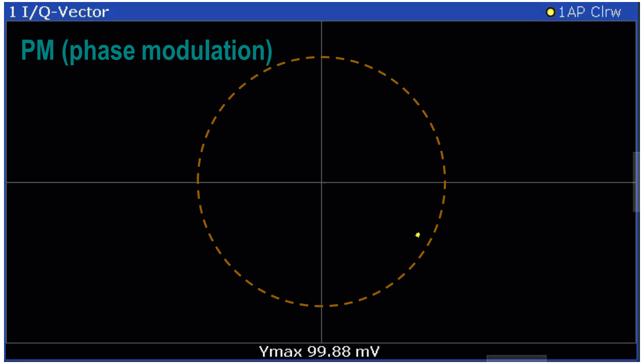
- Every point on display represents a specific magnitude and phase (phasor diagram)
- Magnitude is the distance from center of the plot and indicates linear voltage
- Phase is relative to a reference local oscillator or clock
- Converting Mag and Phase to rectangular (Cartesian) coordinates results in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

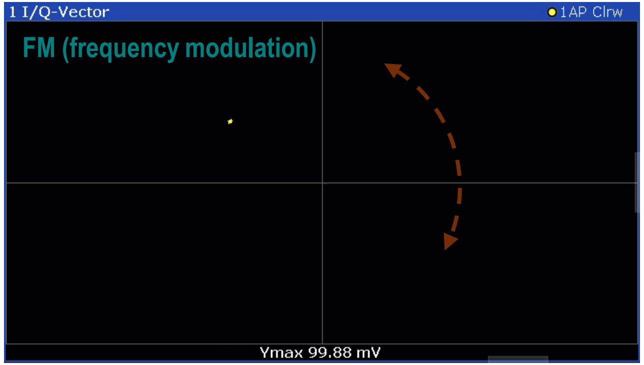


Analog Modulation on Polar Display



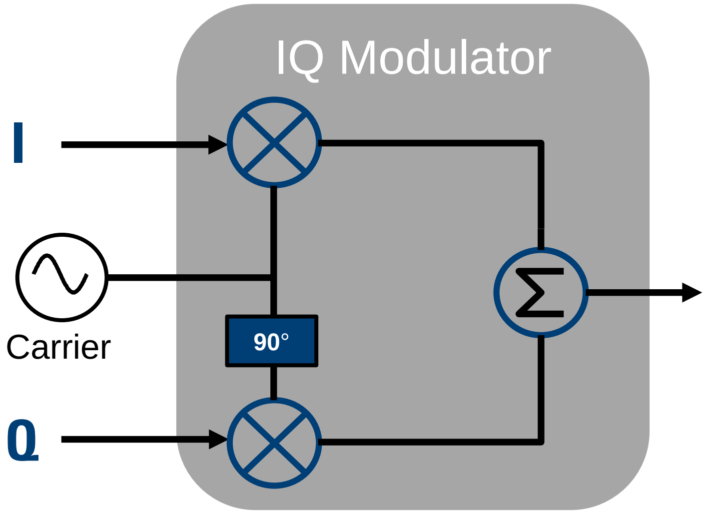






IQ Modulator

- 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)



IQ Modulation – CW Demonstration

► We can use an IQ modulator to create a CW signal with a specific amplitude (A) and phase (ϕ)

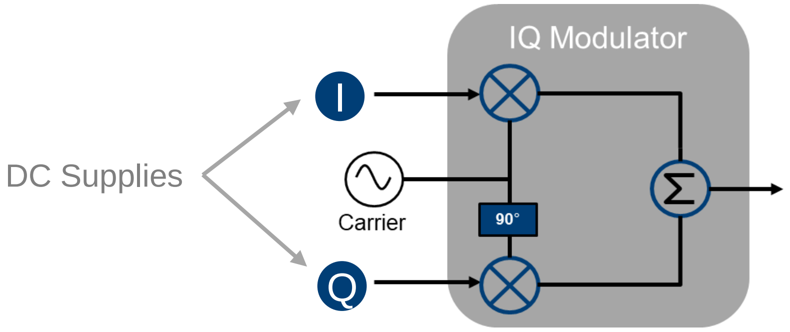
– $I = A\cos(\phi)$ $Q = A\sin(\phi)$

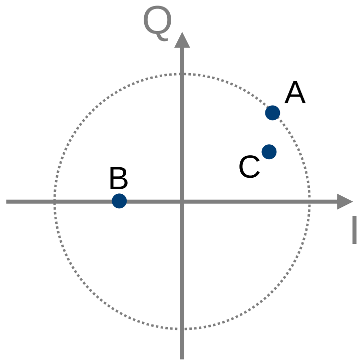
► Examples (assuming 1 V max input to modulator so 'A' ranges from -1 to +1 V):

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

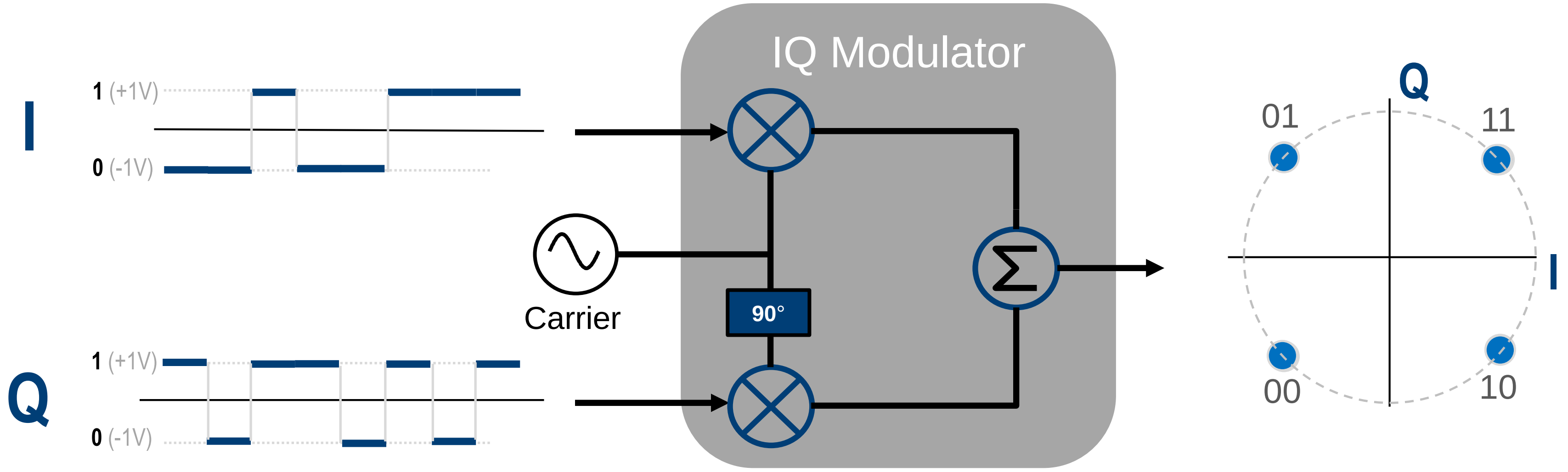
C. -3 dB (A=.707) at 30º: I = 0.612 V, Q = 0.354 V



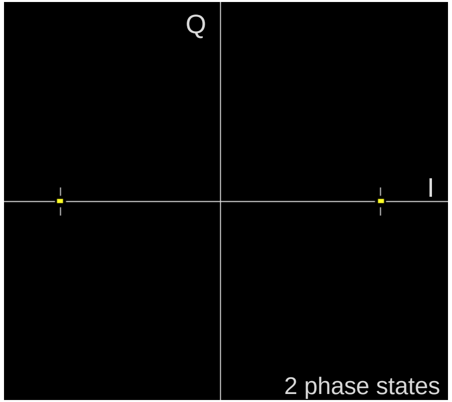


Modulating Digital Data onto a Carrier

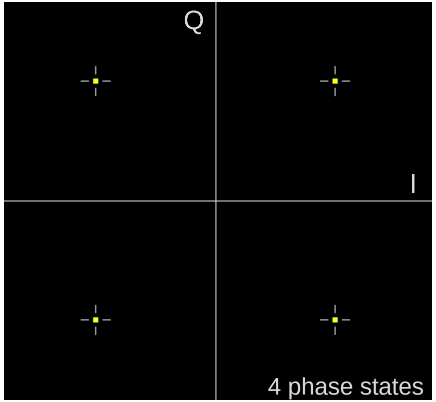
- We want to transmit the following hex data bytes: 4 D 3 B
- In binary this is: 0100 1101 0011 1011
- In this example, we route the first bit to ‘I’ and the second bit to ‘Q’, then repeat with next bits



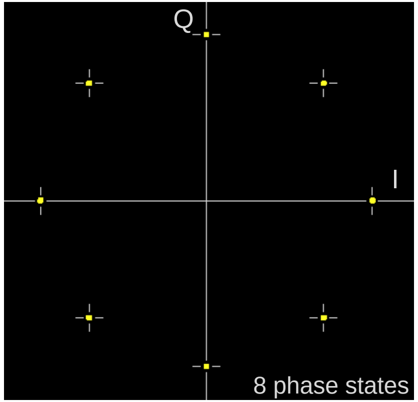
Digital Phase Modulation: Phase Shift Keying (PSK)



BPSK
(Binary Phase Shift Keying)



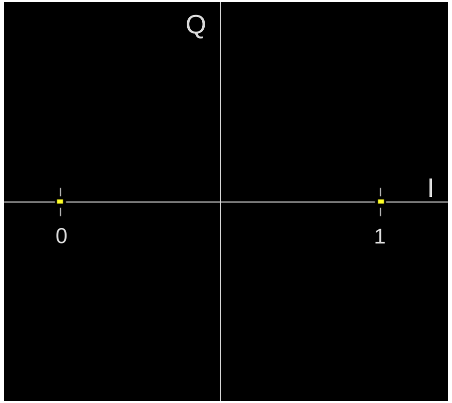
QPSK
(Quadrature Phase Shift Keying)



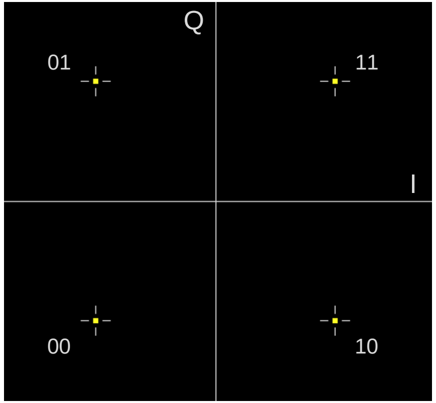
8PSK
(8 State Phase Shift Keying)

Constellation Diagrams

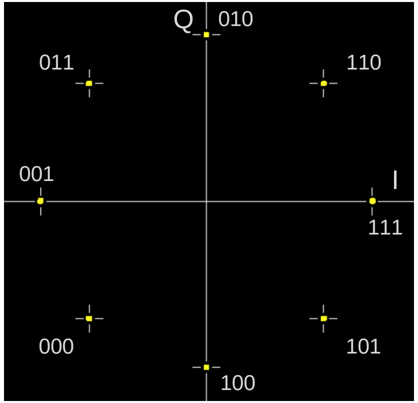
Bit Rate vs. Symbol Rate



BPSK
(1 bit/symbol)



QPSK
(2 bits/symbol)



8PSK
(3 bits/symbol)

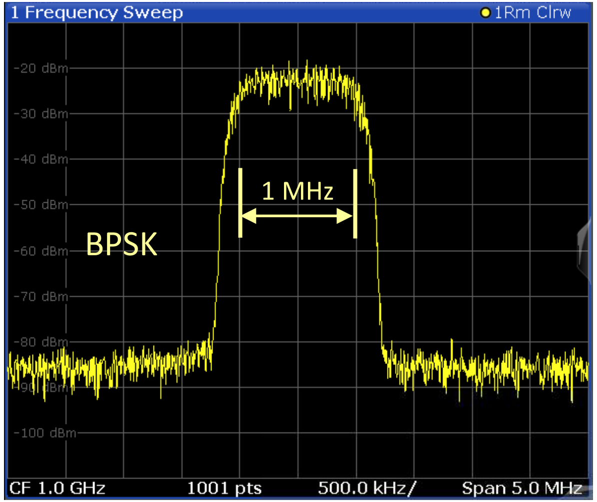
Bit Rate: frequency of the system bit stream

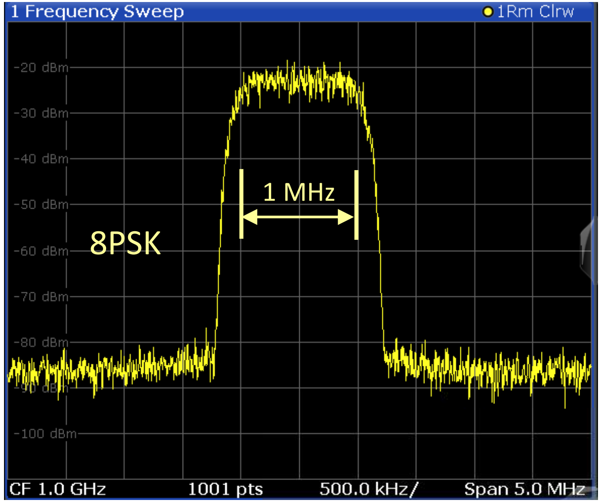
Symbol Rate: bit rate divided by bits per symbol (also called Baud Rate*)

*named for Émile Baudot – telecommunications pioneer

Spectral Bandwidth, Bit Rate, and Symbol Rate

► Signal Bandwidth depends on <u>symbol</u> rate, not bit rate





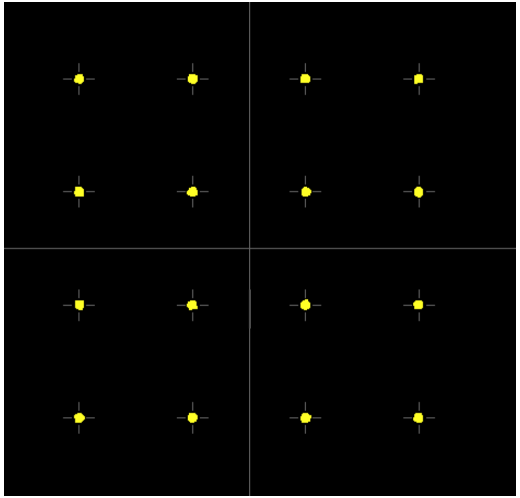
BPSK: 1 bit / symbol
1 Msps = **1 Mbps**

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

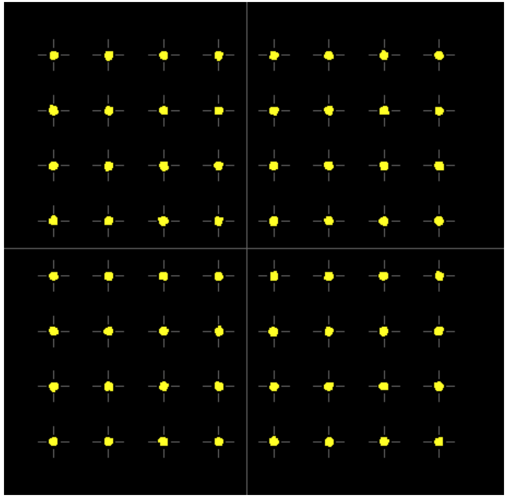
Higher order modulation formats transmit higher bit rate in same bandwidth

Quadrature Amplitude Modulation (QAM)

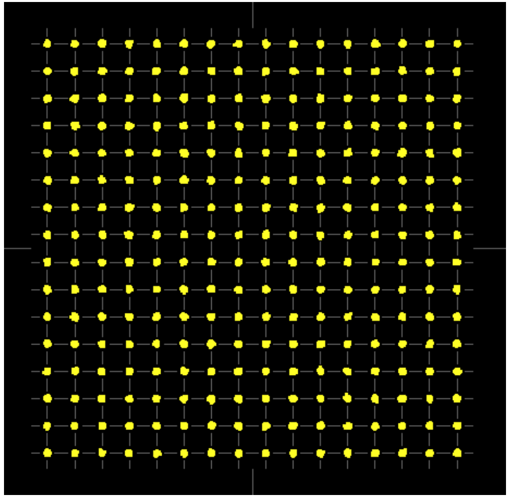
- Other QAM Orders: 32, 128, 512, 1024, 2048, 4096, 8192, 16384
- QPSK is sometimes called 4QAM



16QAM
(4 bits per symbol)



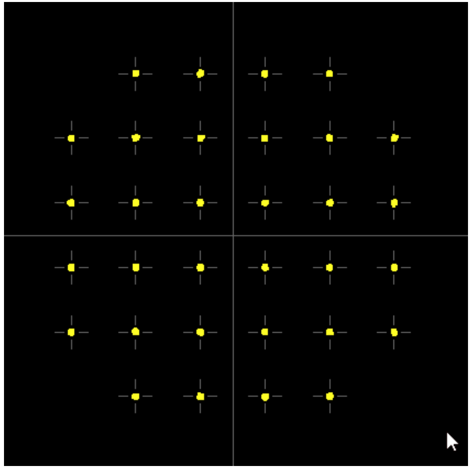
64QAM
(6 bits per symbol)



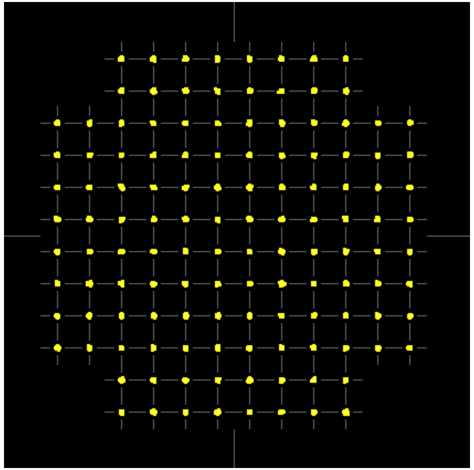
256QAM
(8 bits per symbol)

Odd-Order QAM

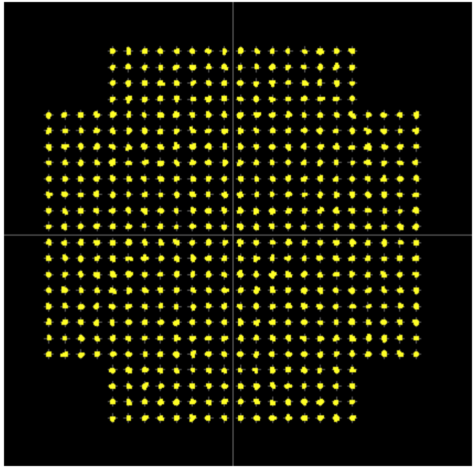
- Standard QAM has orders that are powers of 2 and perfect squares: 16, 64, 256, 1024, 4096, etc.
- Odd-order QAM has orders that are power of 2 and not perfect squares: 32, 128, 512, 2048, etc.
- Symbols are removed from the constellation to force the number of symbols to be a power of 2
- Corner symbols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



32QAM
(5 bits per symbol)



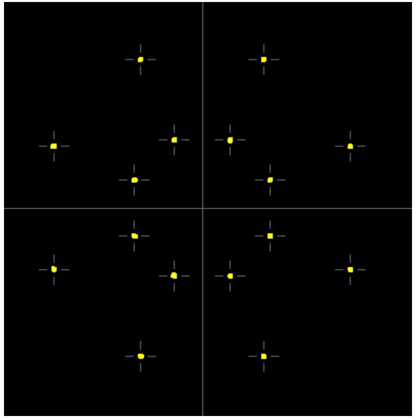
128QAM
(7 bits per symbol)



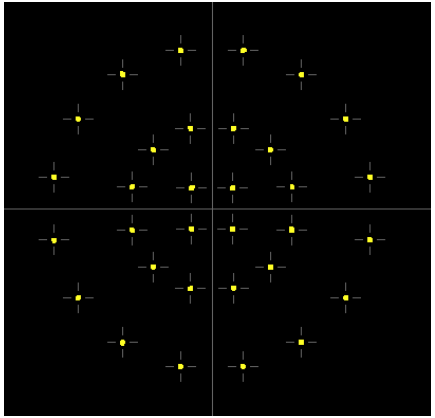
512QAM
(9 bits per symbol)

APSK Modulation (Amplitude Phase Shift Keying)

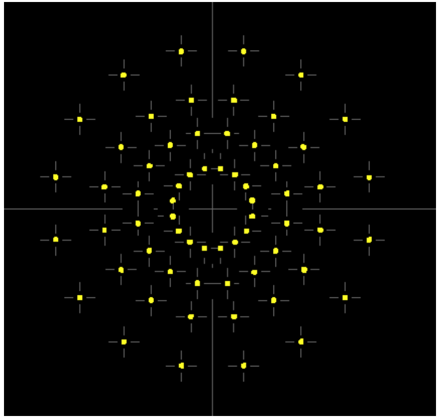
- Constellation symbols are arranged in concentric rings
- Robust against amplifier compression
- Commonly used in satellite communications, DVB-S2, DVB-S2X, etc.



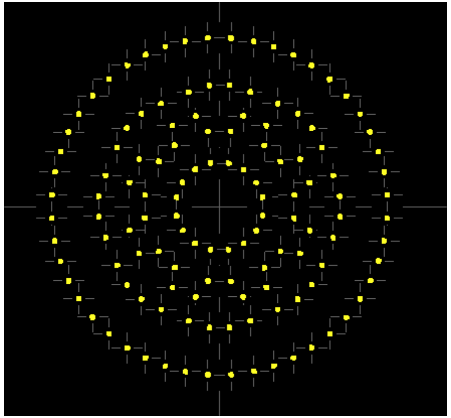
16APSK



32APSK



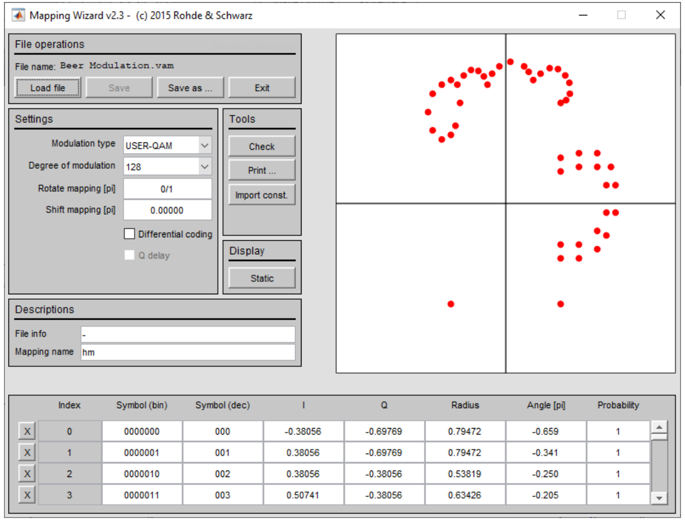
64APSK



128APSK

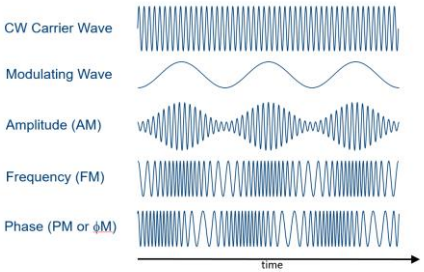
Constellations can be Arbitrary!

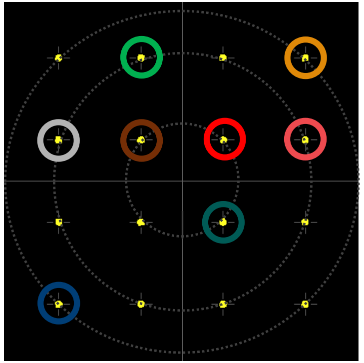
► R&S Mapping Wizard

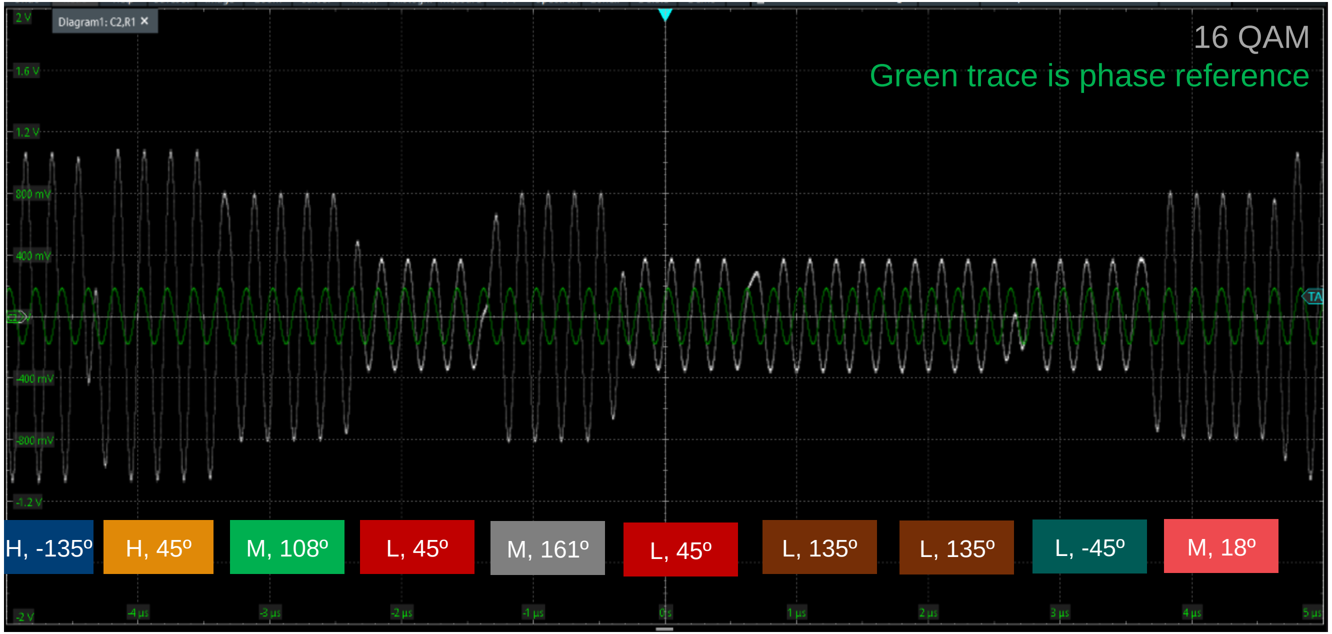


16 QAM in Time Domain

- We've seen what AM, FM, and ϕM look like in time-domain
- What does 16 QAM look like?

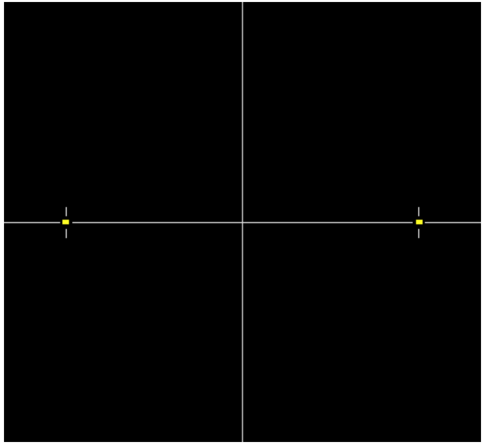




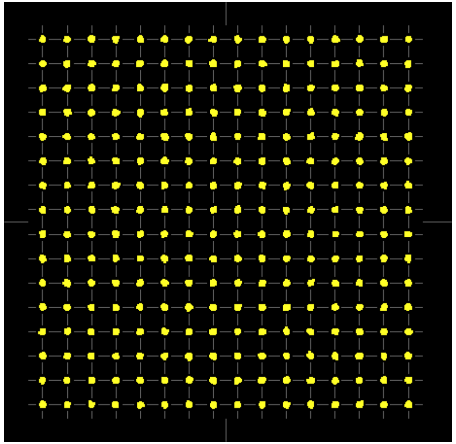


High Order vs. Low Order Modulation

- 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, imperfect transmitters, and signal path (channel) impairments



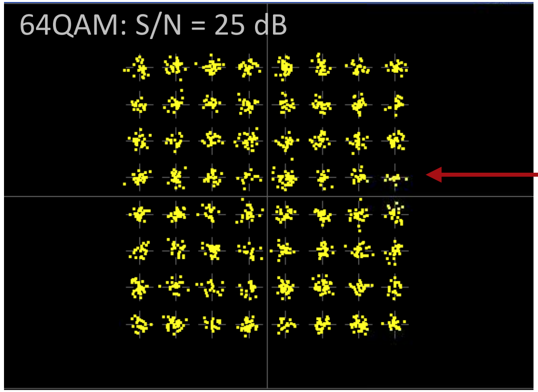
BPSK
(1 bit per symbol)



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 20 dB) this simplifies to $C = 0.332 * B * S/N_{dB}$

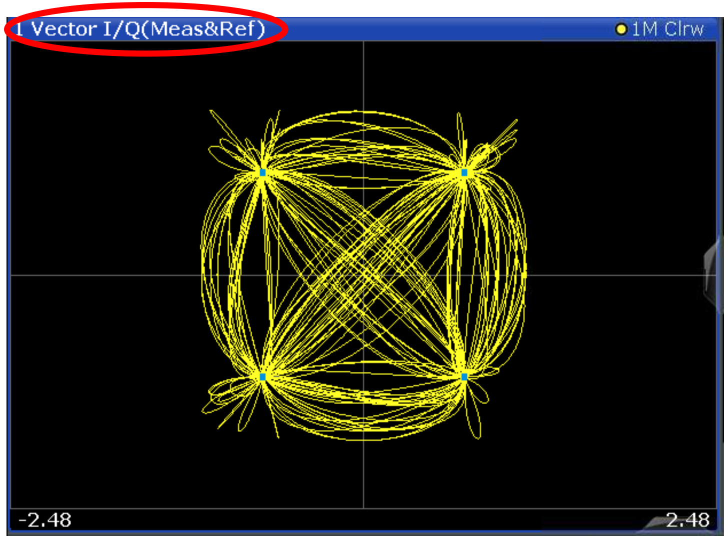


Higher probability of symbol (bit) error with same S/N ratio

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

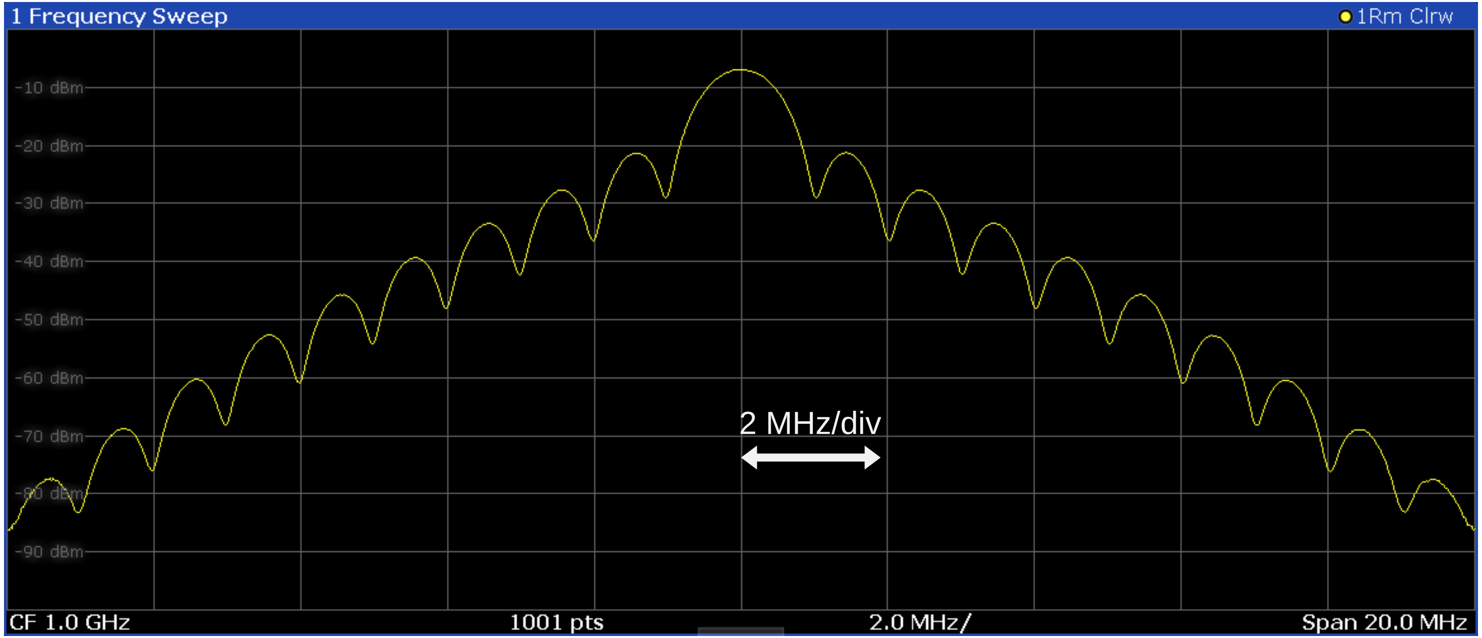
Constellation Diagram
(IQ location at symbol clock times)



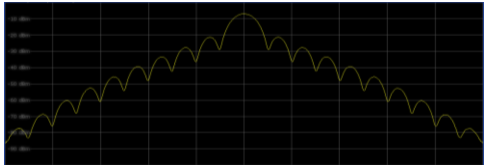
Vector Diagram
(IQ location at symbol clock and during transitions)

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

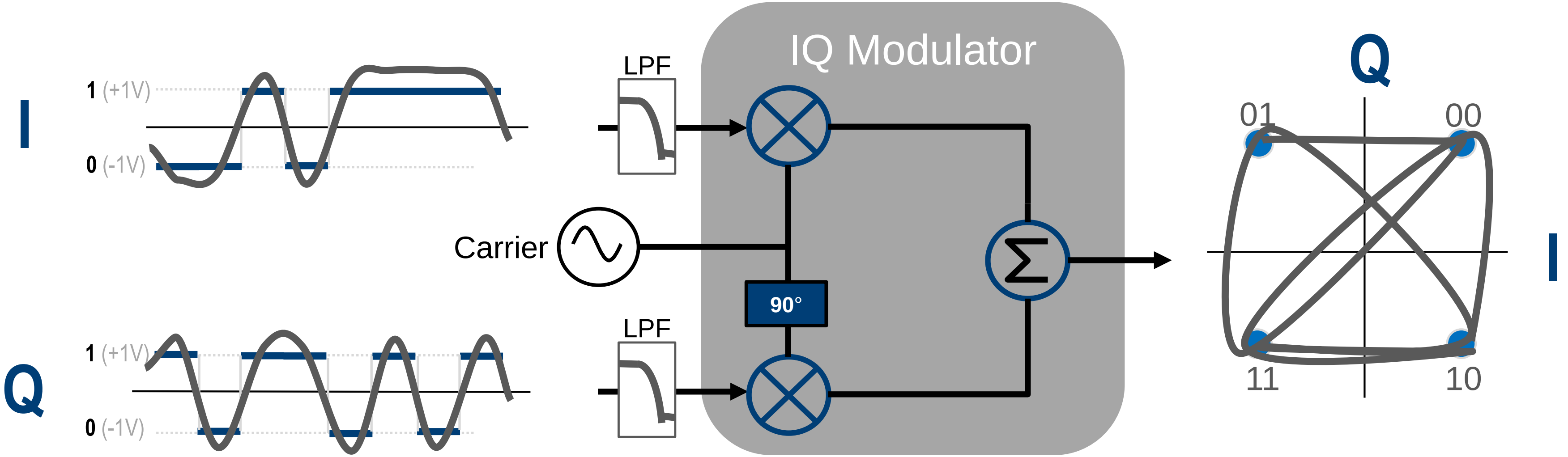
► How can we limit the occupied bandwidth of this 1 Msym/s signal?



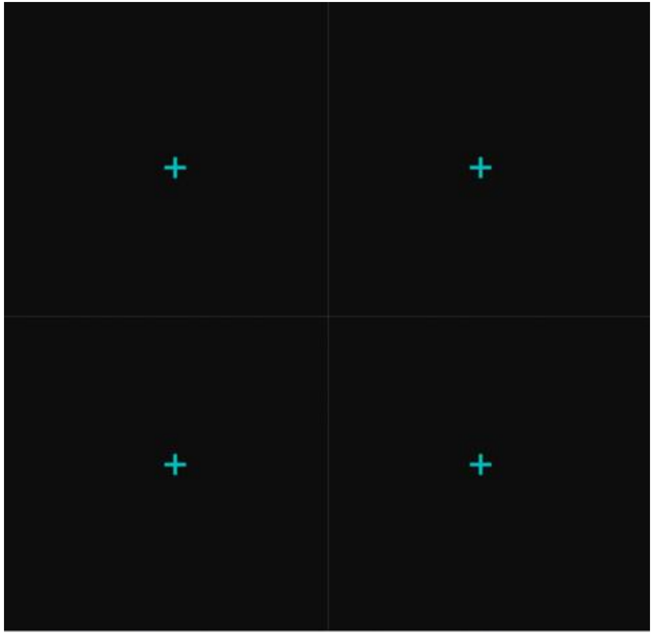
Filtering



- 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

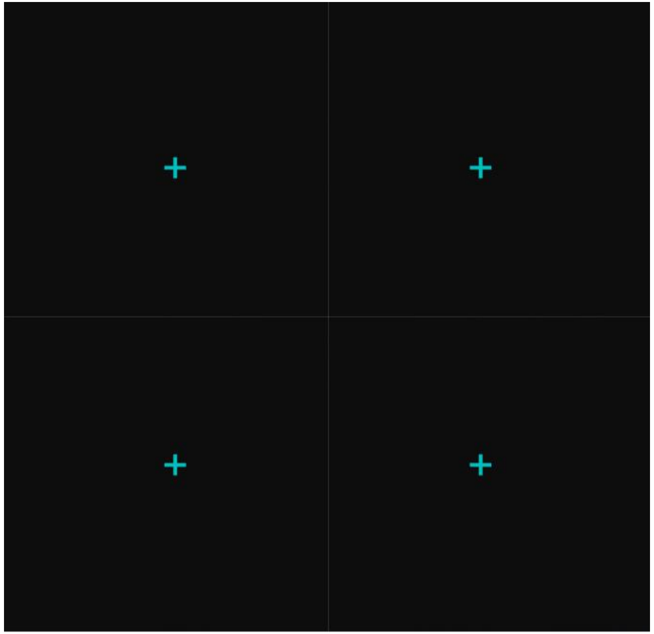


IQ Vector Diagram in Slo-Mo



QPSK with high phase noise

IQ Vector Diagram in Slo-Mo

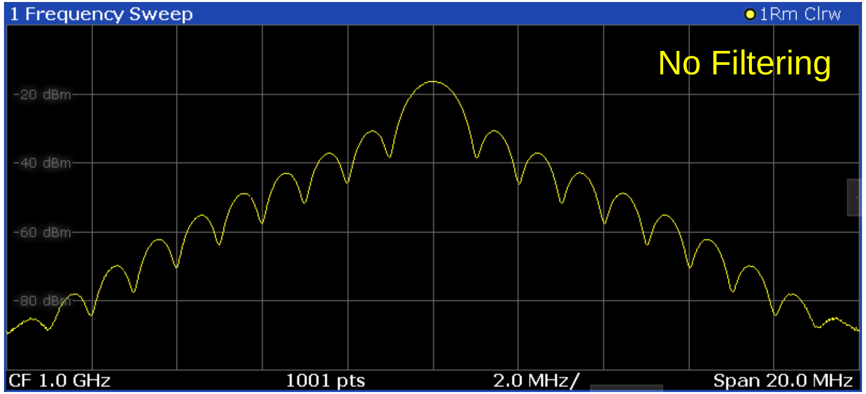


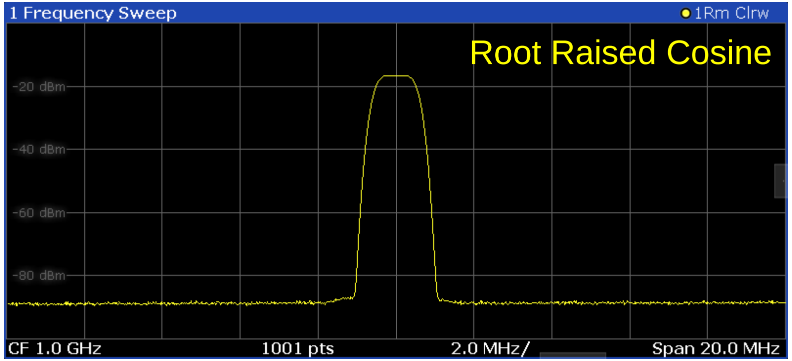
QPSK with high phase noise

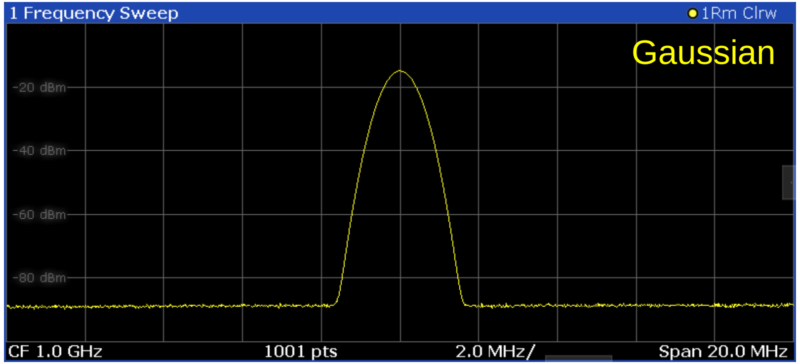
Who has played with one of these?

IQ with Etch-a-Sketch

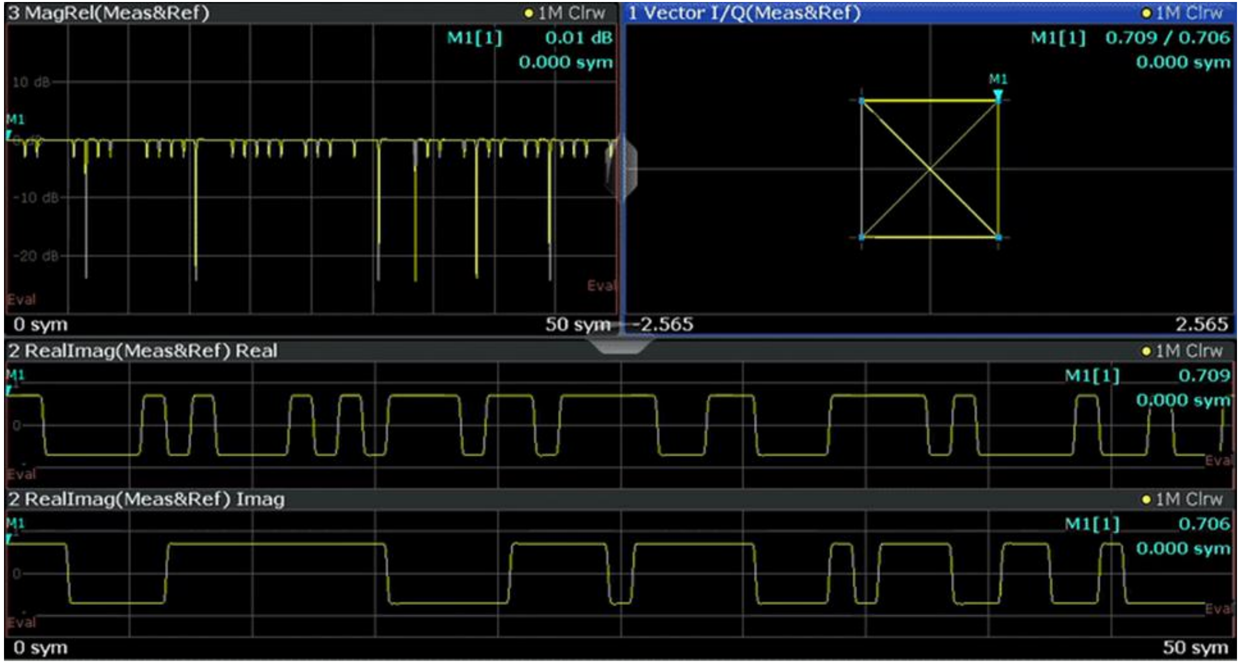
Spectrum with some Common Filter Types
QPSK 1 Msps



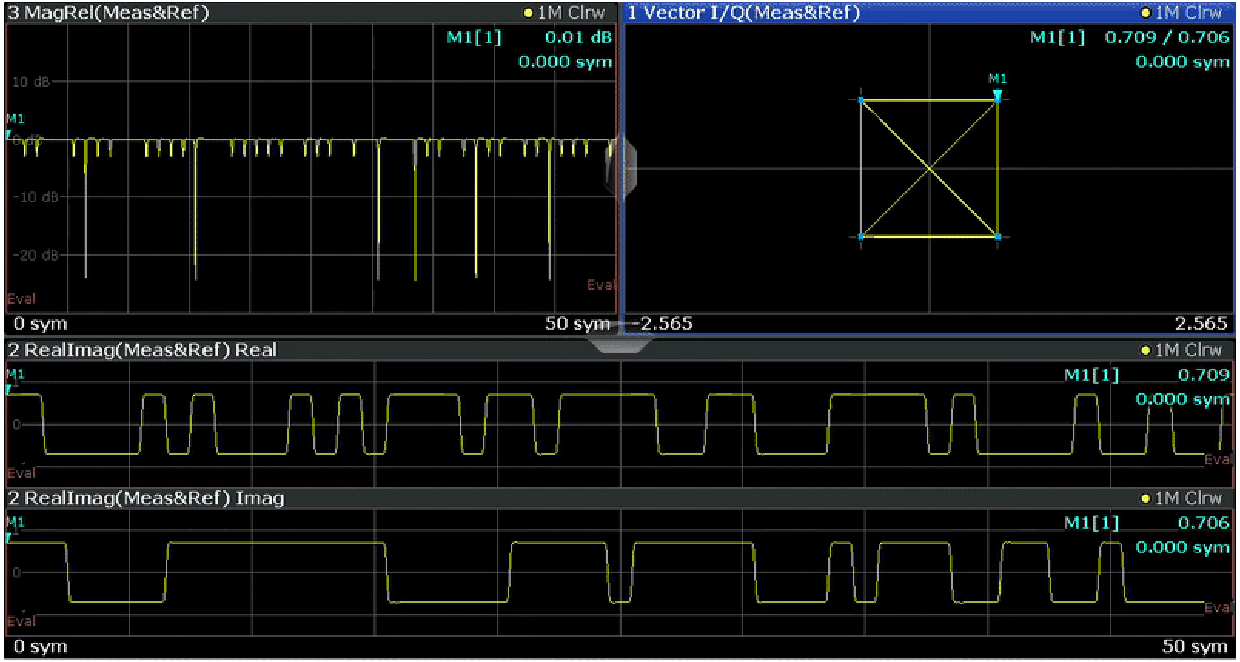




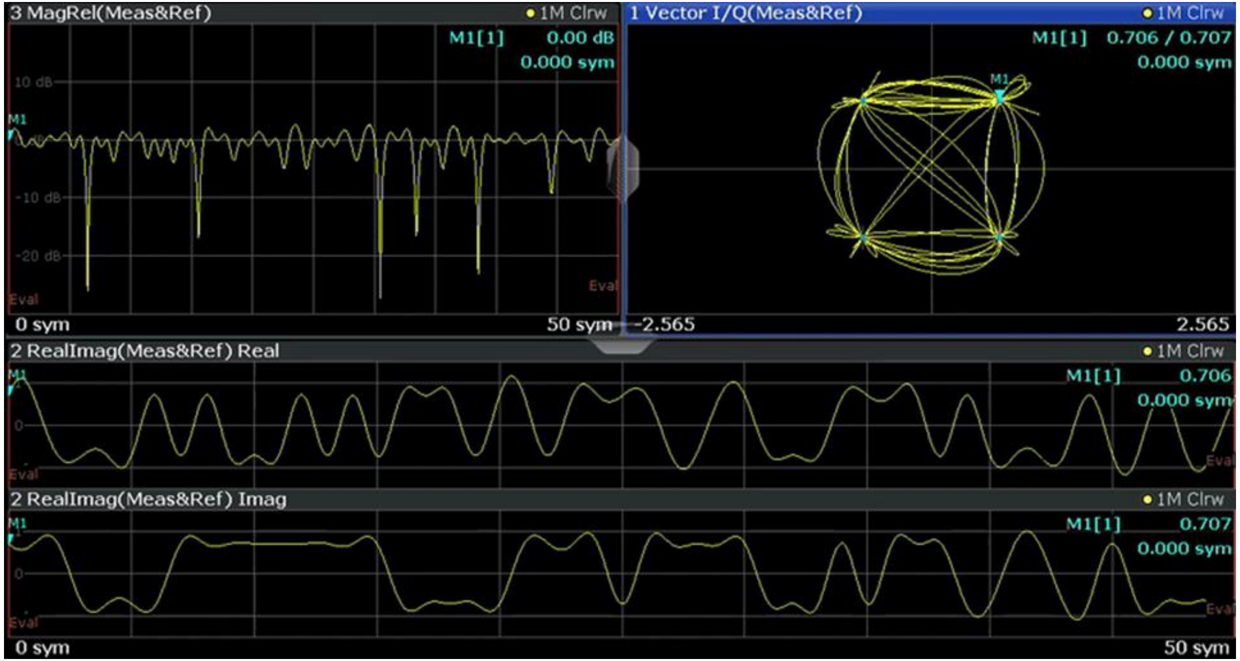
QPSK signal with no filtering



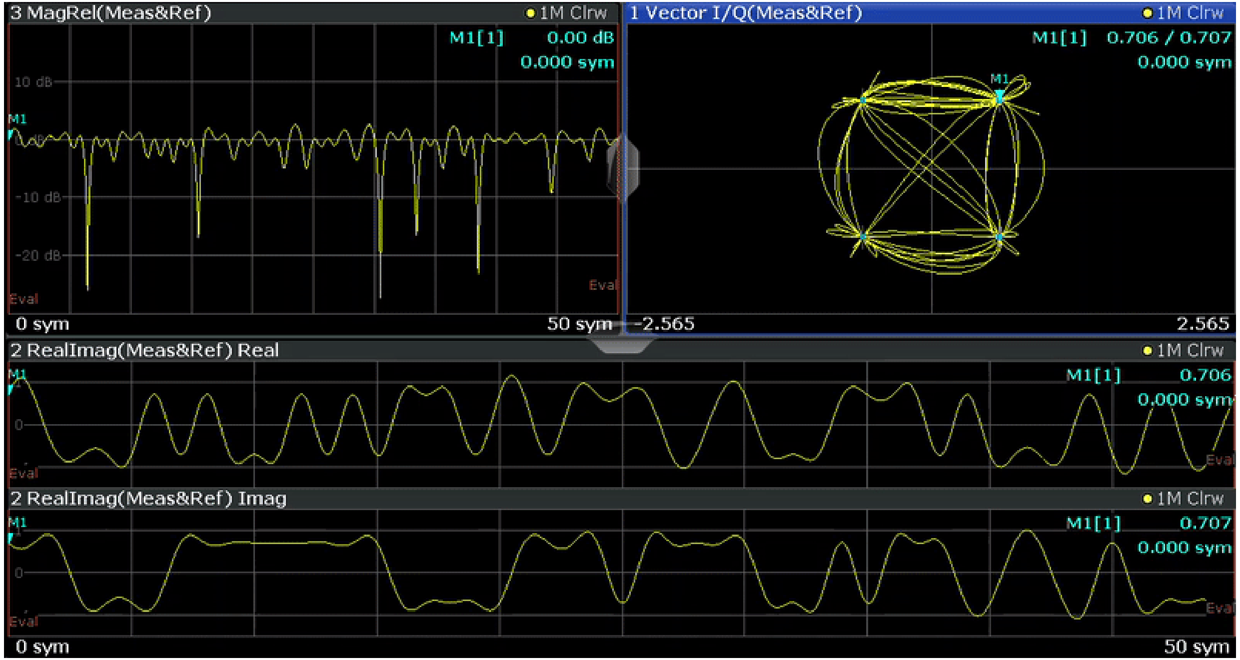
QPSK signal with no filtering



QPSK signal with RRC filtering

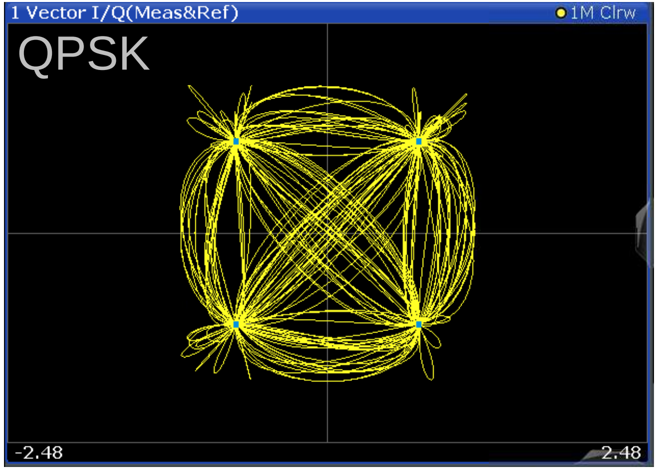


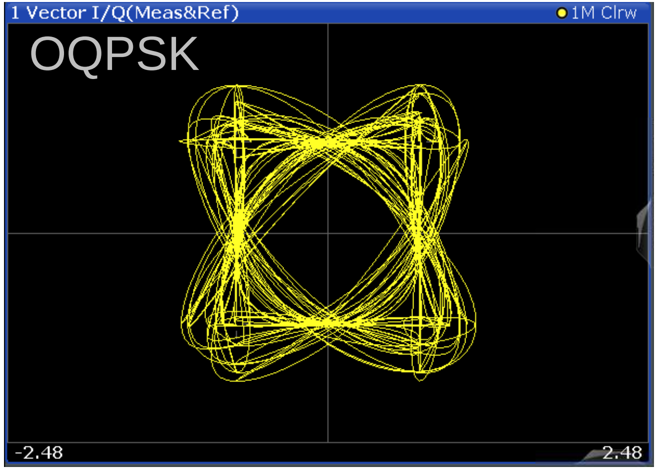
QPSK signal with RRC filtering



Reducing Peak / Avg Ratio (Crest Factor)

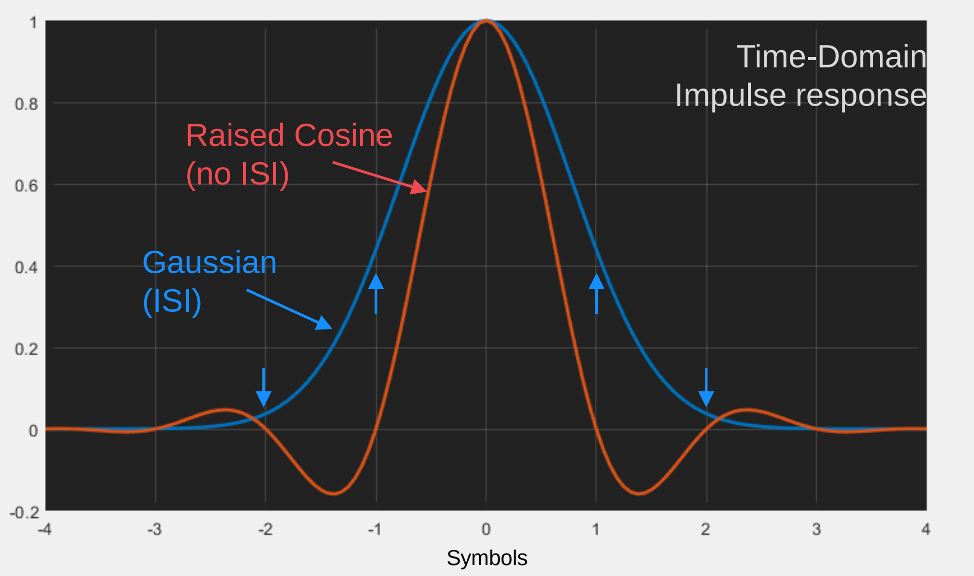
- OQPSK (Offset QPSK)
  - I and Q baseband signals are offset from each other by ½ symbol
  - I changes then Q changes then I changes, etc.
  - I and Q don’t transition at the same time so the center is avoided (reduces pk/avg ratio)
  - Lower cost, less linear amplifiers can be used





Inter-Symbol Interference (ISI)

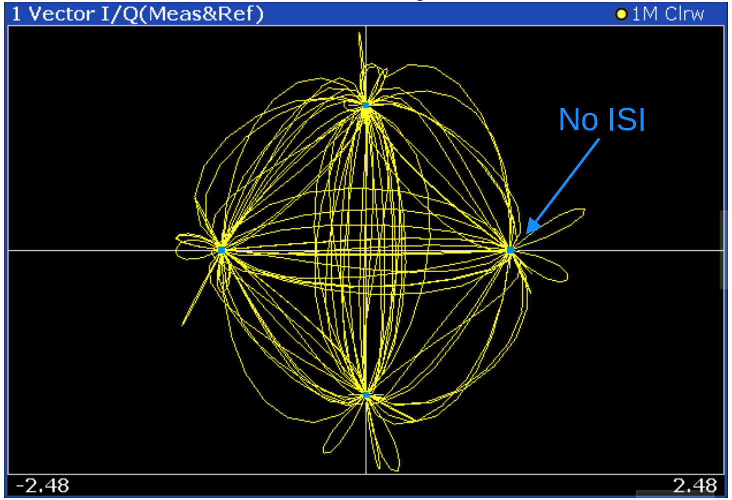
- If the time-domain impulse response of the filter is non-zero at adjacent symbols, ISI occurs
- A filter with ISI causes the IQ position of the signal to be dependent on previous and subsequent symbols
- ISI-free filters are called “Nyquist” filters – Raised Cosine (RC) is an example of an ISI-free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



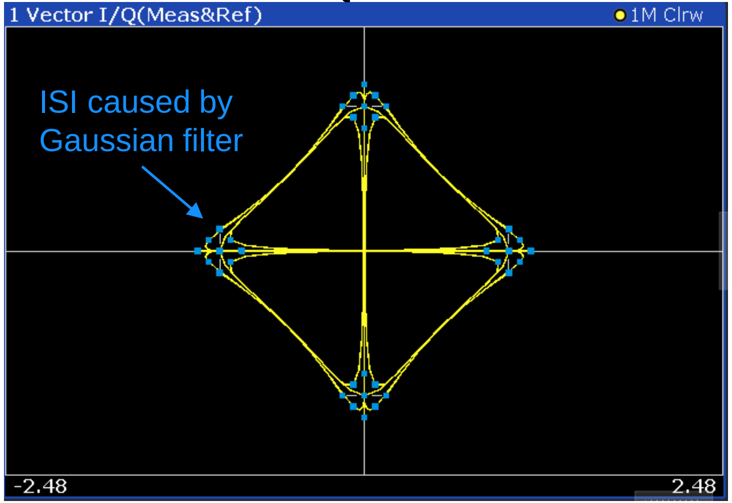
Inter-Symbol Interference (ISI)

- 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



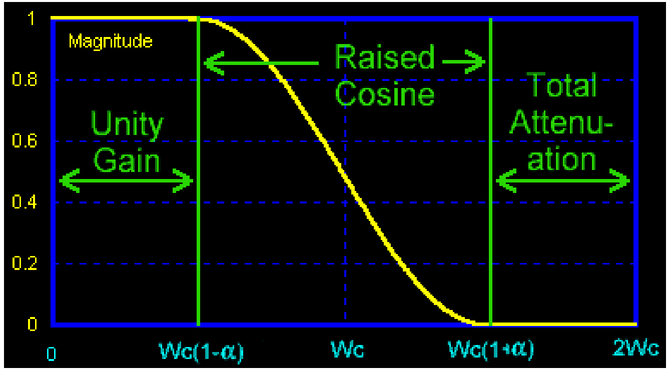
Gaussian filtered QPSK with obvious ISI



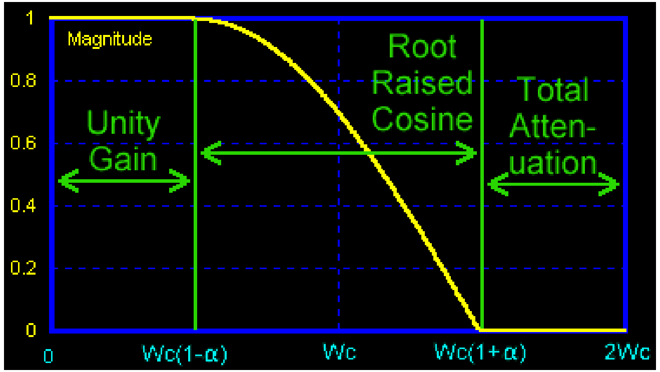
Digital Modulation: RC and RRC Filters

- 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

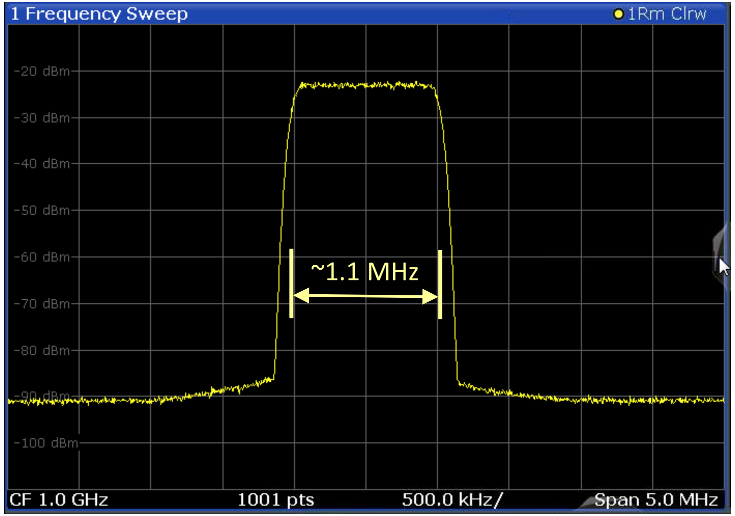


RRC – Root Raised Cosine

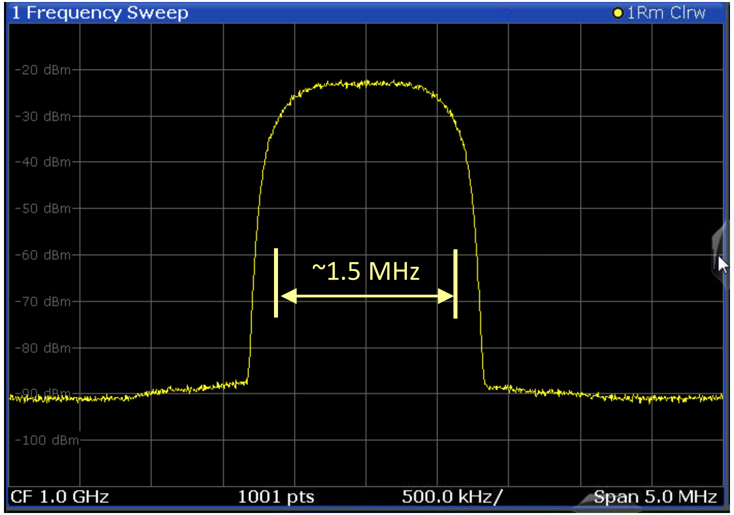


Frequency response

RRC Filter Alpha: Effect on Bandwidth



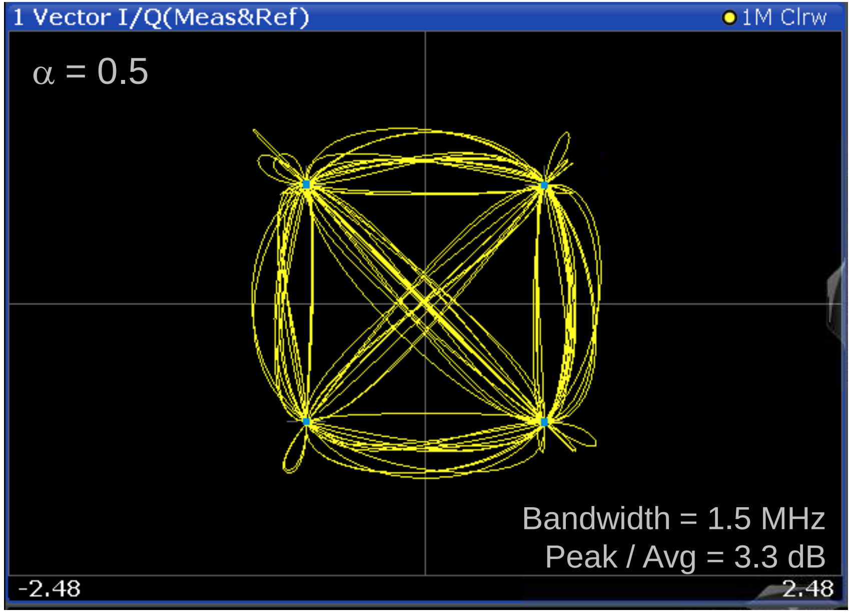
1Msps, RRC, α = .1



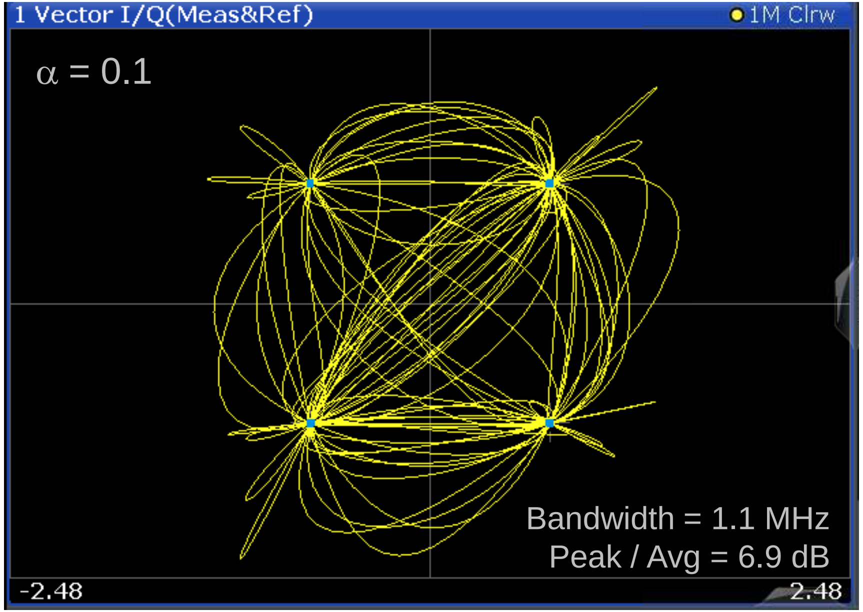
1Msps, RRC, α = .5

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

RRC Filter Alpha: Effect on Peak/Avg Ratio



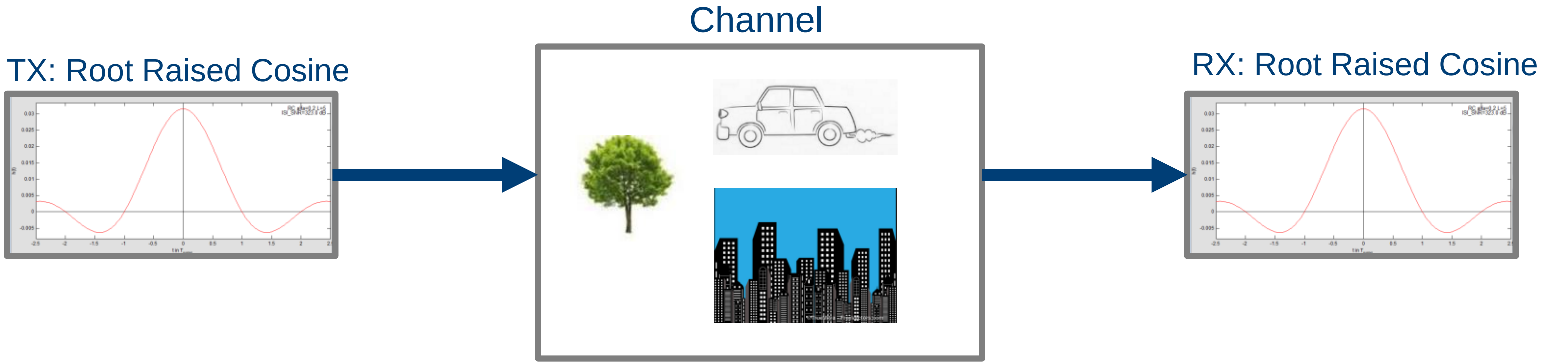
Smaller peaks → Lower Peak/Avg
Sharper transitions → Higher BW



Larger peaks → Higher Peak/Avg
Smoother transitions → Lower BW

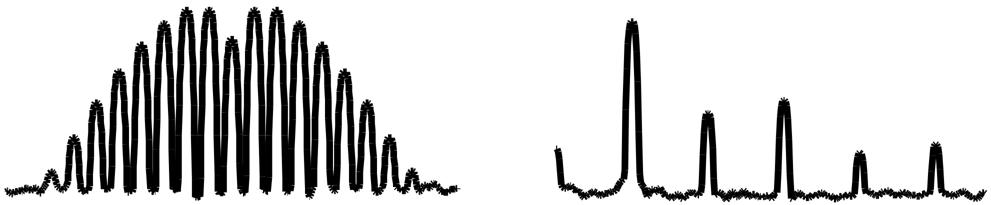
Why Use ‘Root’ Raised Cosine Filters?

- 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



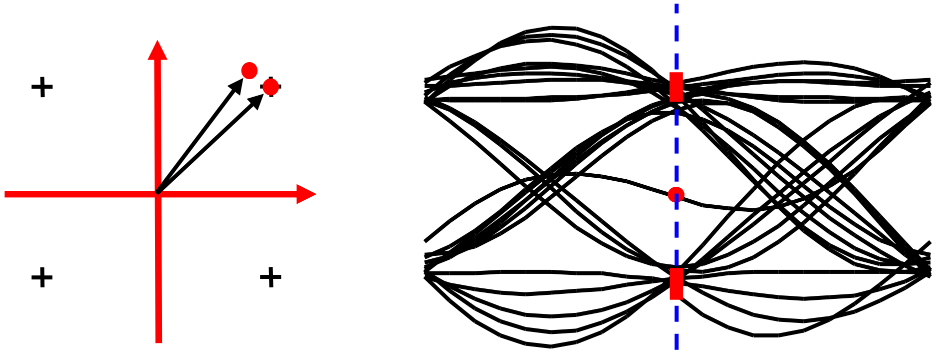
Modulation Quality Measurements

Analog Modulation



FM Deviation, AM Depth, Audio Distortion, etc.

Digital Modulation

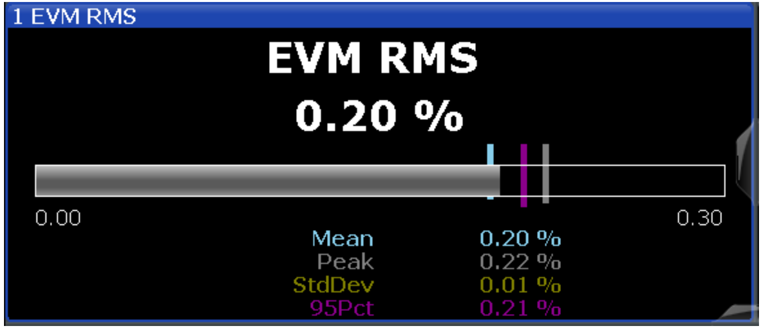


EVM, Eye Diagrams, IQ offset (carrier feedthrough), etc.

Digital Modulation Quality Measurements

- EVM (Error Vector Magnitude)
  - Single figure of merit for quantifying digital modulation quality
  - EVM is a measurement of deviation from ideal signal
  - Measured at one symbol or averaged over many
  - Expressed as % or dB
  - Very commonly used in industry

So, what is EVM?

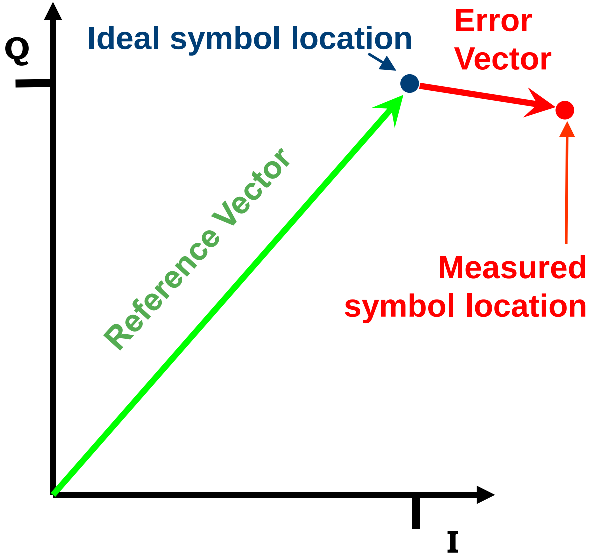


What is EVM?

- The 'error vector' is the vector between the measured symbol location and the ideal location
- EVM is the ratio of the magnitude of the error vector to the magnitude of the reference vector
- The 'reference vector' represents the RMS level of the constellation in the IQ plane
- EVM can be expressed in units of % or dB

$$EVM = \frac{|\,error\,|}{|\,ref\,|} * 100 \quad (\%)$$

$$EVM = 20*\log\left(\frac{|\,error\,|}{|\,ref\,|}\right) \quad (dB)$$



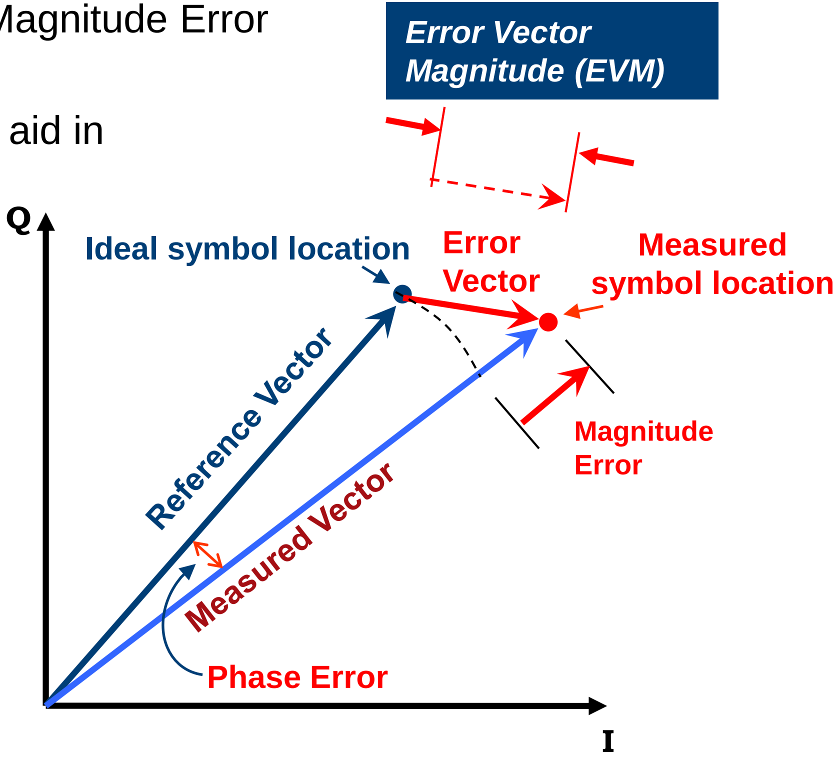
What is EVM?

- EVM can be broken down into its components of Magnitude Error and Phase Error
- The relative contribution of these components can aid in troubleshooting EVM issues

1 Result Summary

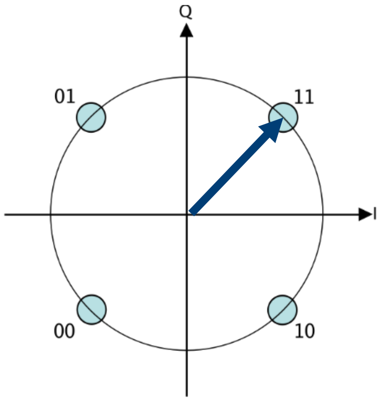
		Current	Peak	Unit
EVM	RMS	0.19	0.22	%
	Peak	0.43	0.56	%
MER	RMS	54.65	53.34	dB
	Peak	47.36	45.05	dB
Phase Error	RMS	0.08	0.09	deg
	Peak	-0.23	0.32	deg
Magnitude Error	RMS	0.13	0.16	%
	Peak	0.36	0.52	%

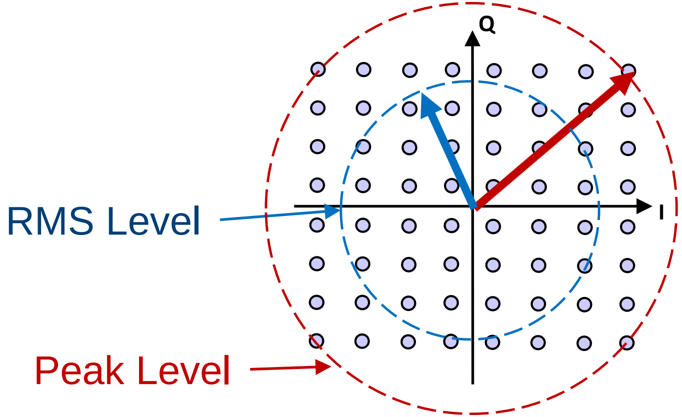
MER (Modulation Error Ratio) is EVM expressed in dB



EVM Reference Vector

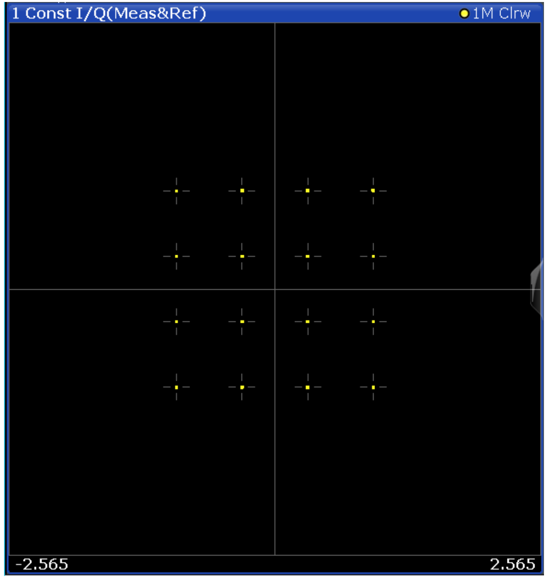
- The ‘reference vector’ is obvious for PSK constellations
- What is the ‘reference vector’ for QAM constellations?
- QAM reference vector can be defined as the peak level or the RMS level of the constellation
- RMS is most common, but must make sure this is setting is correct in the measuring analyzer (VSA)
- Using Peak as reference results in a lower EVM value





Troubleshooting Common Issues using VSA

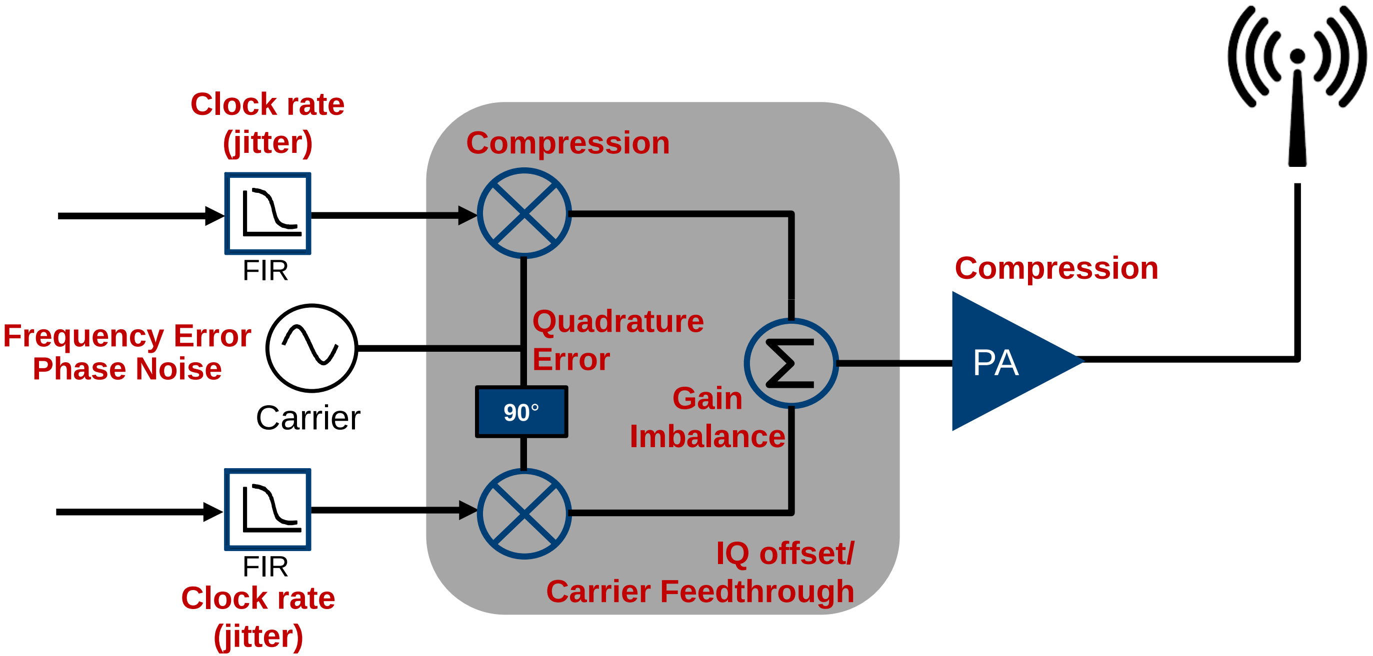
- EVM gives an overall figure of merit for the modulation quality of a signal
- High EVM can be caused by one or more underlying issues – how to troubleshoot?
- The VSA Constellation and Result Summary displays help troubleshoot root causes of high EVM
  - IQ Offset
  - IQ Gain Imbalance
  - Quadrature Offset
  - Low S/N
  - Phase Noise
  - Compression
  - In-channel Spurious
  - Symbol Rate Error



5 Result Summary

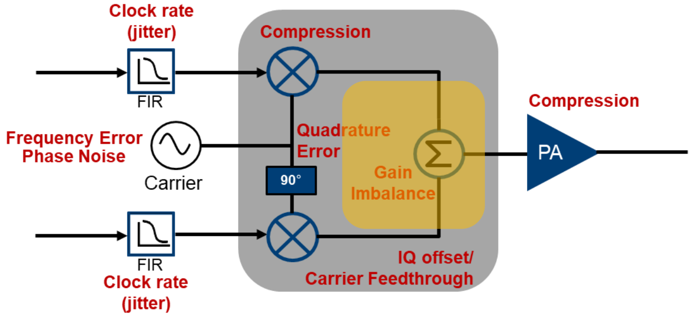
		Current	Peak	Unit
EVM	RMS	0.13	0.13	%
	Peak	0.35	0.44	%
MER	RMS	57.65	57.65	dB
	Peak	49.06	47.04	dB
Phase Error	RMS	0.07	0.07	deg
	Peak	-0.33	-0.39	deg
Magnitude Error	RMS	0.09	0.09	%
	Peak	-0.28	0.30	%
Carrier Frequency Error		20959.10	20959.17	Hz
Symbol Rate Error		-0.06	-0.11	ppm
I/Q Skew		---	---	ps
Rho		0.999 998	0.999 998	
I/Q Offset		-19.21	-19.16	dB
I/Q Imbalance		-23.24	-23.23	dB
Gain Imbalance		0.99	0.99	dB
Quadrature Error		4.43	4.44	deg
Amplitude Droop		-0.000 00	0.000 000	dB/sym
Power		3.20	3.26	dBm

Sources of Modulation Error



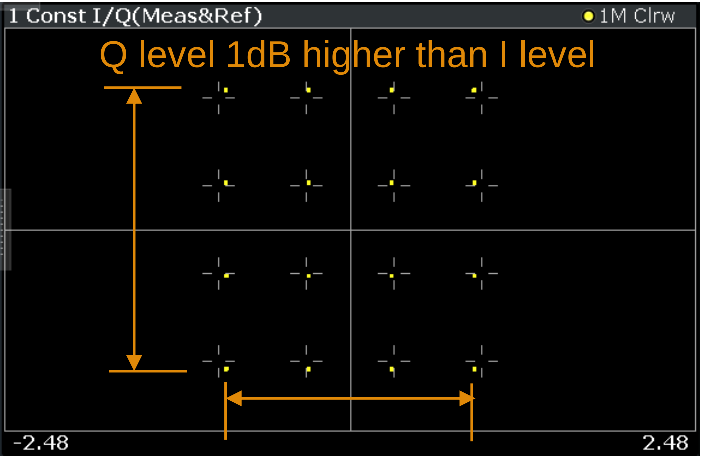
IQ Gain (or Amplitude) Imbalance

- ► Caused by unequal gain between I and Q paths



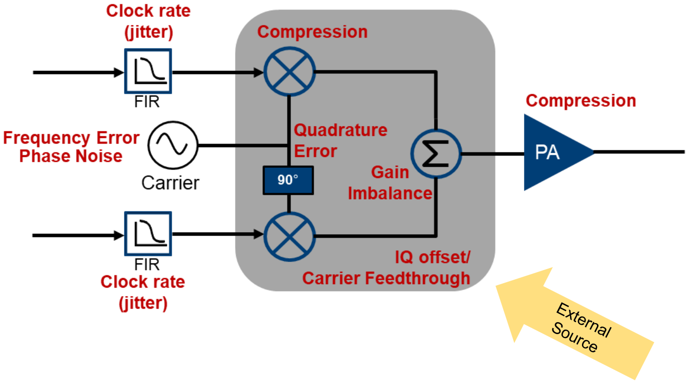
2 Result Summary

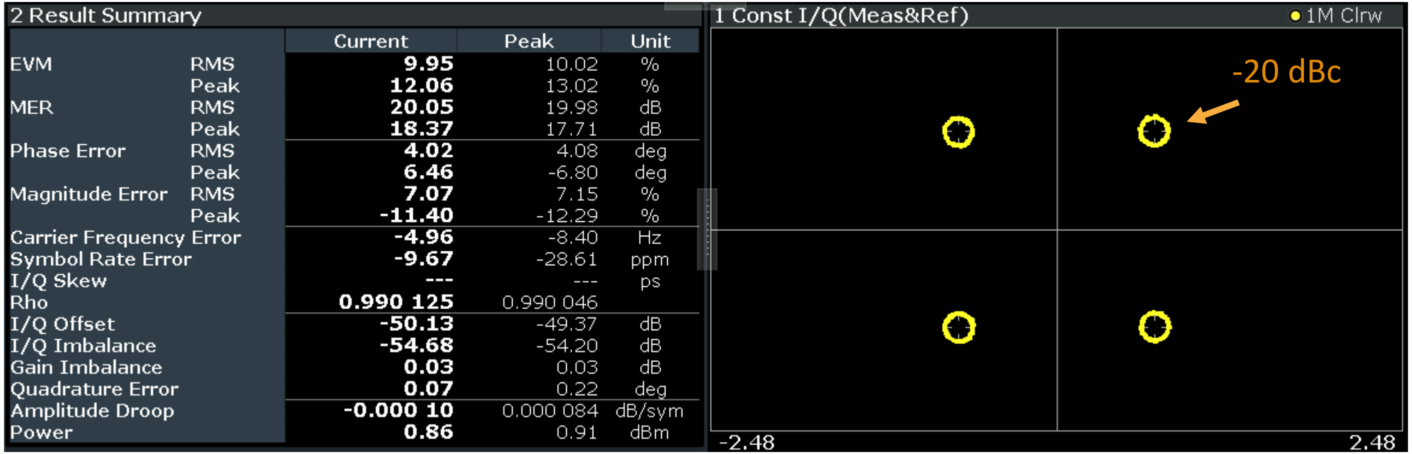
		Current	Peak	Unit
EVM	RMS	5.73	5.73	%
	Peak	7.97	8.04	%
MER	RMS	24.84	24.84	dB
	Peak	21.97	21.89	dB
Phase Error	RMS	2.71	2.72	deg
	Peak	-3.88	-3.90	deg
Magnitude Error	RMS	3.22	3.29	%
	Peak	5.05	5.07	%
Carrier Frequency Error		-3.04	-3.06	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.996 734	0.996 729	
I/Q Offset		-60.78	-60.70	dB
I/Q Imbalance		-24.85	-24.84	dB
Gain Imbalance		1.00	1.00	dB
Quadrature Error		0.06	0.06	deg
Amplitude Droop		0.000 000	0.000 001	dB/sym
Power		0.14	0.18	dBm



In-Band Spurious

- Spurious CW signal within the channel bandwidth will cause the constellation points to have a 'donut' shape
- Easy to identify in constellation diagram
- Typical source is switching power supply clock or other oscillator in the DUT leaking into the IQ modulator

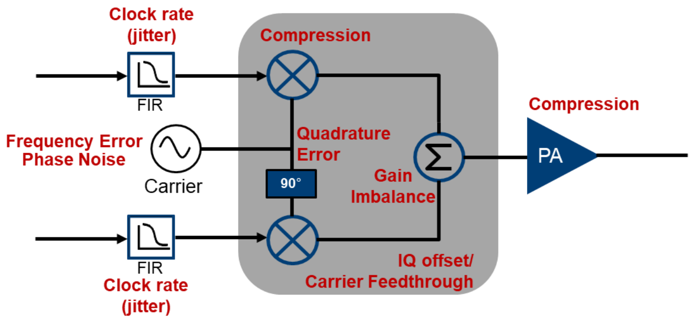




2 Result Summary

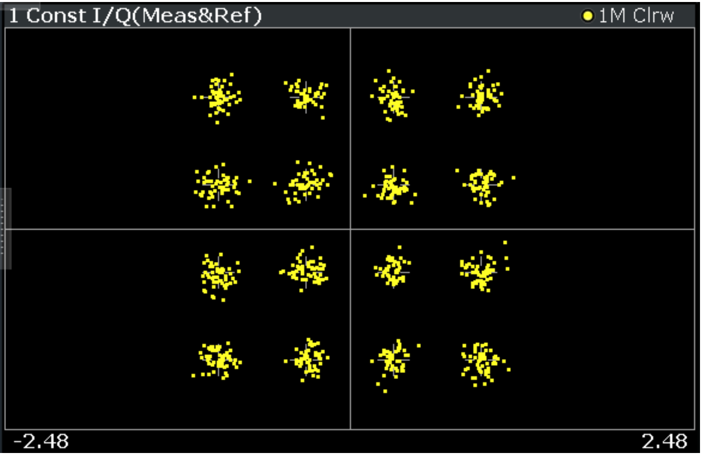
		Current	Peak	Unit
EVM	RMS	9.95	10.02	%
	Peak	12.06	13.02	%
MER	RMS	20.05	19.98	dB
	Peak	18.37	17.71	dB
Phase Error	RMS	4.02	4.08	deg
	Peak	6.46	-6.80	deg
Magnitude Error	RMS	7.07	7.15	%
	Peak	-11.40	-12.29	%
Carrier Frequency Error		-4.96	-8.40	Hz
Symbol Rate Error		-9.67	-28.61	ppm
I/Q Skew		---	---	ps
Rho		0.990 125	0.990 046	
I/Q Offset		-50.13	-49.37	dB
I/Q Imbalance		-54.68	-54.20	dB
Gain Imbalance		0.03	0.03	dB
Quadrature Error		0.07	0.22	deg
Amplitude Droop		-0.000 10	0.000 084	dB/sym
Power		0.86	0.91	dBm

Low Signal to Noise Ratio
SNR: 20 dB



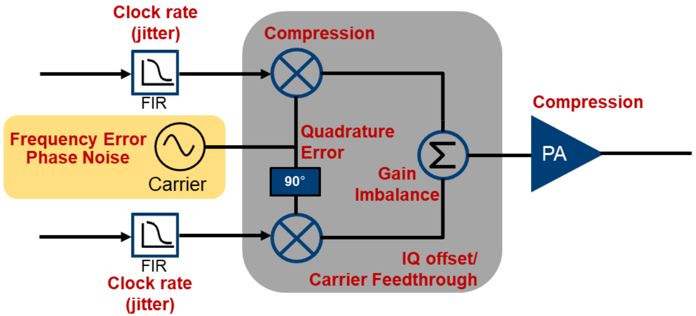
2 Result Summary

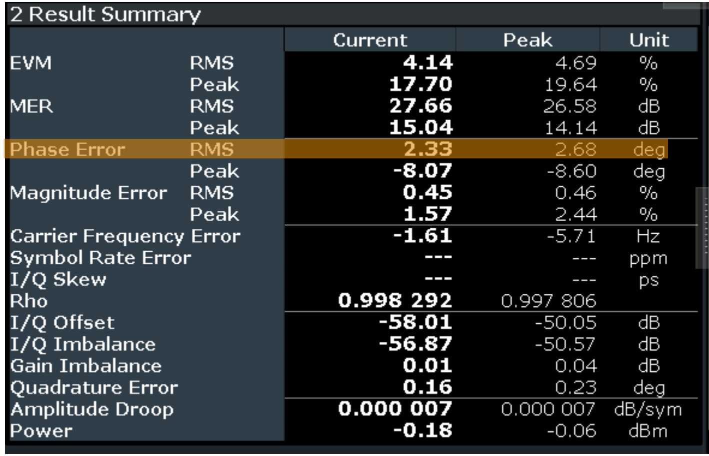
		Current	Peak	Unit
EVM	RMS	9.77	10.22	%
	Peak	27.97	35.46	%
MER	RMS	20.20	19.81	dB
	Peak	11.07	9.01	dB
Phase Error	RMS	5.72	5.88	deg
	Peak	-25.78	-34.49	deg
Magnitude Error	RMS	6.85	7.33	%
	Peak	23.76	-34.60	%
Carrier Frequency Error		-1.37	-5.04	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.990 527	0.989 678	
I/Q Offset		-47.52	-39.96	dB
I/Q Imbalance		-65.46	-42.31	dB
Gain Imbalance		0.01	0.05	dB
Quadrature Error		0.00	0.88	deg
Amplitude Droop		-0.000 01	0.000 109	dB/sym
Power		-0.01	0.03	dBm



Phase Noise

- ▶ Phase noise forms arcs of noise at the symbol points
- ▶ Caused by high phase noise in LO/carrier
- ▶ Also indicated by high Phase Error value (relative to Mag Error)

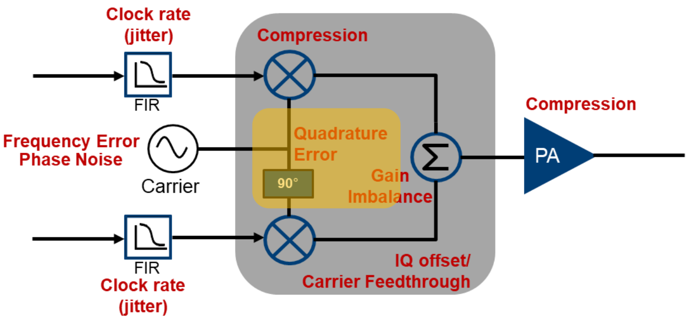




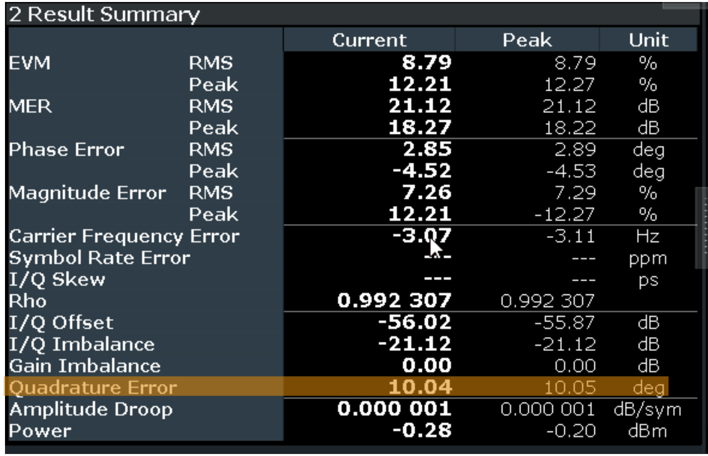
2 Result Summary

		Current	Peak	Unit
EVM	RMS	4.14	4.69	%
	Peak	17.70	19.64	%
MER	RMS	27.66	26.58	dB
	Peak	15.04	14.14	dB
Phase Error	RMS	2.33	2.68	deg
	Peak	-8.07	-8.60	deg
Magnitude Error	RMS	0.45	0.46	%
	Peak	1.57	2.44	%
Carrier Frequency Error		-1.61	-5.71	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.998 292	0.997 806	
I/Q Offset		-58.01	-50.05	dB
I/Q Imbalance		-56.87	-50.57	dB
Gain Imbalance		0.01	0.04	dB
Quadrature Error		0.16	0.23	deg
Amplitude Droop		0.000 007	0.000 007	dB/sym
Power		-0.18	-0.06	dBm

Quadrature Error

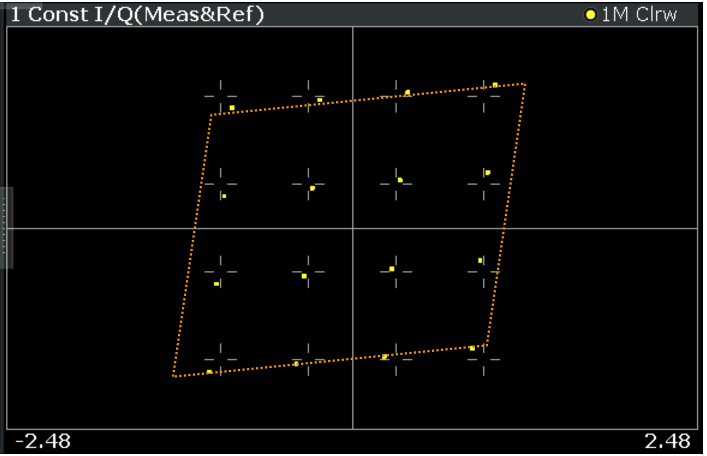


- Quadrature error results when the angle between I and Q is not 90 degrees
- This impairment changes the constellation from a square to a parallelogram
- Quadrature error is most easily seen in the Result Summary



2 Result Summary

		Current	Peak	Unit
EVM	RMS	8.79	8.79	%
	Peak	12.21	12.27	%
MER	RMS	21.12	21.12	dB
	Peak	18.27	18.22	dB
Phase Error	RMS	2.85	2.89	deg
	Peak	-4.52	-4.53	deg
Magnitude Error	RMS	7.26	7.29	%
	Peak	12.21	-12.27	%
Carrier Frequency Error		-3.07	-3.11	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.992 307	0.992 307	
I/Q Offset		-56.02	-55.87	dB
I/Q Imbalance		-21.12	-21.12	dB
Gain Imbalance		0.00	0.00	dB
Quadrature Error		10.04	10.05	deg
Amplitude Droop		0.000 001	0.000 001	dB/sym
Power		-0.28	-0.20	dBm



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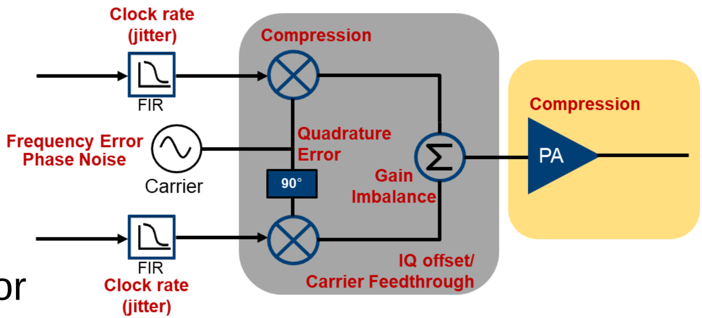
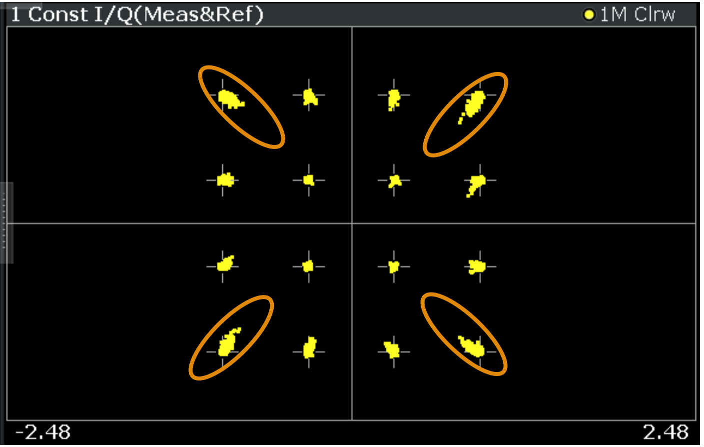
Compression

- Compression has a subtle effect in the constellation – the outermost symbols (those with the highest power level) are smeared toward the origin
- Compression can result from overdriving the IQ modulator or output amplifier

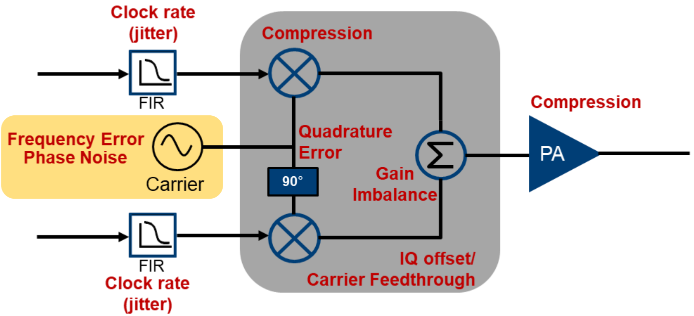


2 Result Summary

		Current	Peak	Unit
EVM	RMS	1.85	1.85	%
	Peak	24.90	24.90	%
MER	RMS	34.65	34.65	dB
	Peak	12.08	12.08	dB
Phase Error	RMS	0.48	0.48	deg
	Peak	-5.45	-5.45	deg
Magnitude Error	RMS	1.69	1.69	%
	Peak	-24.51	-24.51	%
Carrier Frequency Error		-3.34	-3.34	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.999 655	0.999 655	
I/Q Offset		-62.49	-62.49	dB
I/Q Imbalance		-76.68	-76.68	dB
Gain Imbalance		0.00	0.00	dB
Quadrature Error		0.02	0.02	deg
Amplitude Droop		0.000 000	0.000 000	dB/sym
Power		17.02	17.02	dBm



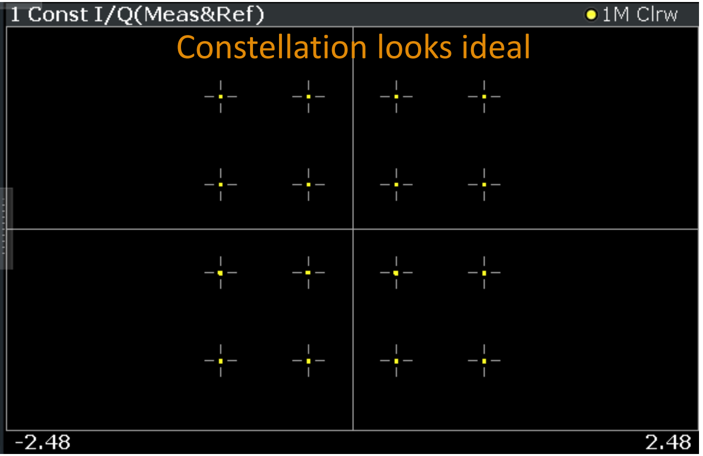
Carrier Frequency Error



- ► Carrier frequency error is simply the difference between the actual and the intended output center frequency
- ► Caused by error in the DUT's frequency reference
- ► Frequency error is not visible in the constellation and must be read in the Result Summary

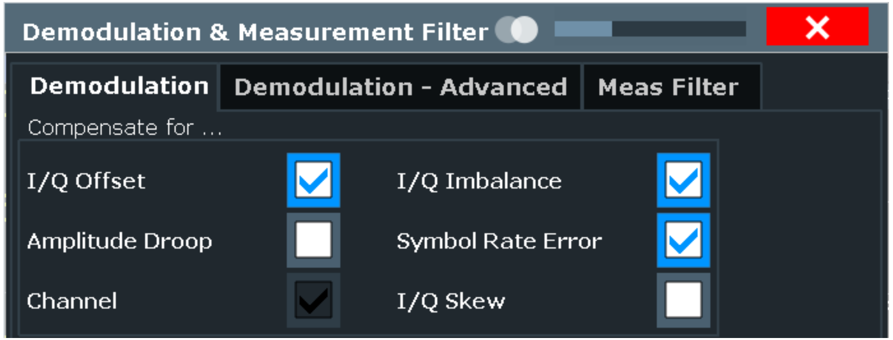
2 Result Summary

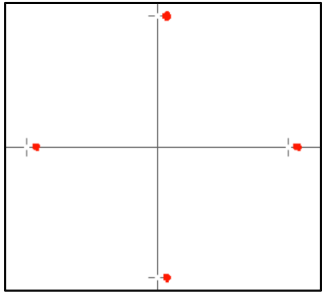
		Current	Peak	Unit
EVM	RMS	0.26	0.26	%
	Peak	0.59	0.62	%
MER	RMS	51.87	51.81	dB
	Peak	44.51	44.17	dB
Phase Error	RMS	0.14	0.14	deg
	Peak	-0.73	-0.75	deg
Magnitude Error	RMS	0.19	0.19	%
	Peak	0.51	0.54	%
Carrier Frequency Error		-5003.43	-5003.46	Hz
Symbol Rate Error		---	---	ppm
I/Q Skew		---	---	ps
Rho		0.999 993	0.999 993	
I/Q Offset		-58.73	-58.44	dB
I/Q Imbalance		-65.02	-64.84	dB
Gain Imbalance		0.01	0.01	dB
Quadrature Error		0.05	0.05	deg
Amplitude Droop		0.000 000	0.000 002	dB/sym
Power		-0.32	-0.26	dBm



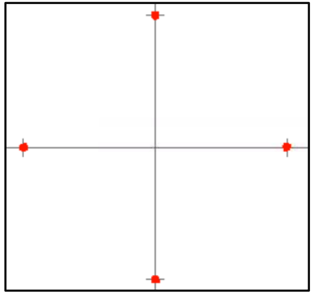
The VSA Can Exclude Some of these Errors from EVM

- Why do this, isn't it cheating?
- If the receiver in the DUT is insensitive to certain types of errors, then it makes sense not to include them in the EVM value
- Only systematic errors can be compensated, not random errors like phase noise or compression





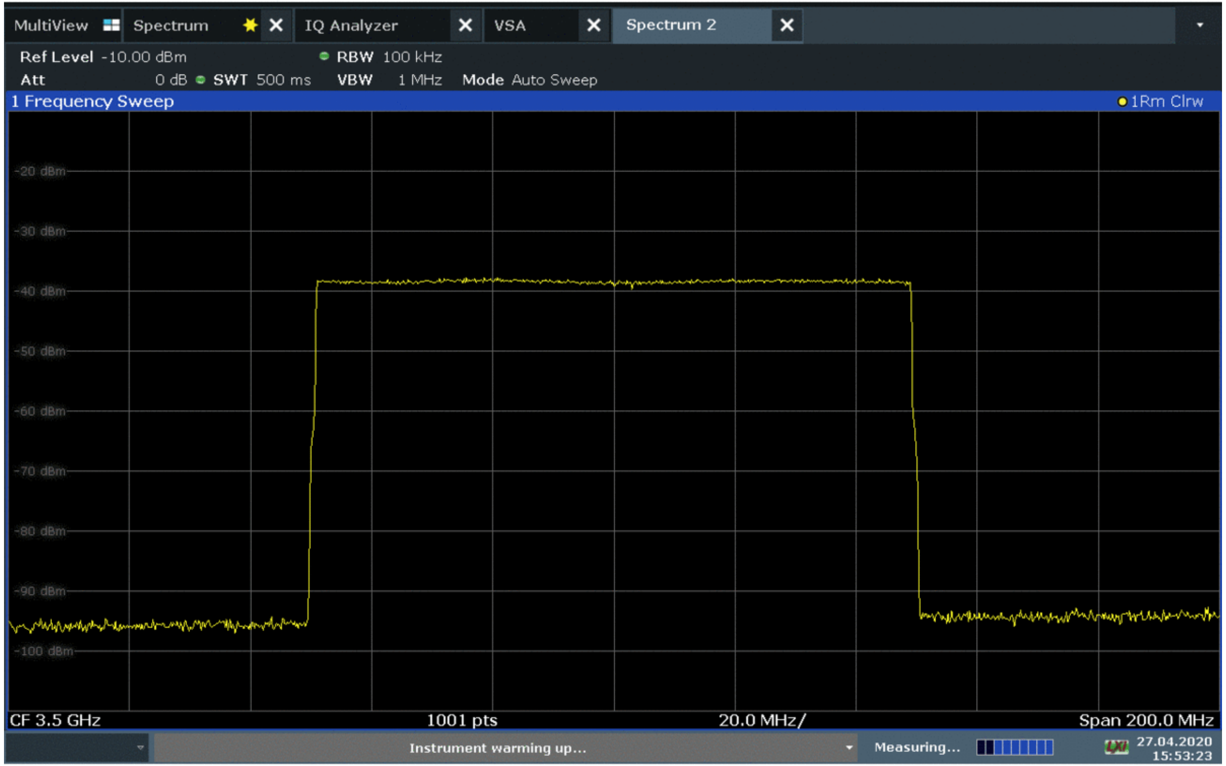
Not Compensated



Compensated

Example: IQ Offset of 2.5%

Example: 100 MHz 5G NR OFDMA Signal



15:53:23 27.04.2020

5G NR Signal Example:

3275 Data carriers

Spaced by 30 kHz

Total bandwidth ~ 98.25 MHz

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
- EVM is a commonly used figure of merit for digital modulation quality
- Constellation diagrams can be used to identify some, but not all, types of impairments

Did we answer the questions?

- What does ‘Digital Modulation’ mean?
- What is ‘IQ’ and why do we use it?
- What is this diagram called? What does it show?
- What is the significance of the blue dots?
- What is that crazy curve that connect the dots?
- What determines the shape of the curve?
- How many types of digital modulation are there?
- How do bit rate, symbol rate, and Baud rate relate?
- How does filtering work?
- What do PSK, QAM, APSK, RRC, ISI, and EVM mean?