VSA – Lunch and Learn

Digital Communications Troubleshooting Using Vector Signal Analysis

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Welcome!

Agenda

- Analog vs Digital
- IQ Modulation
- Filtering
- Digital Communications Measurements
- Quantitative IQ Measurements

Analog vs Digital

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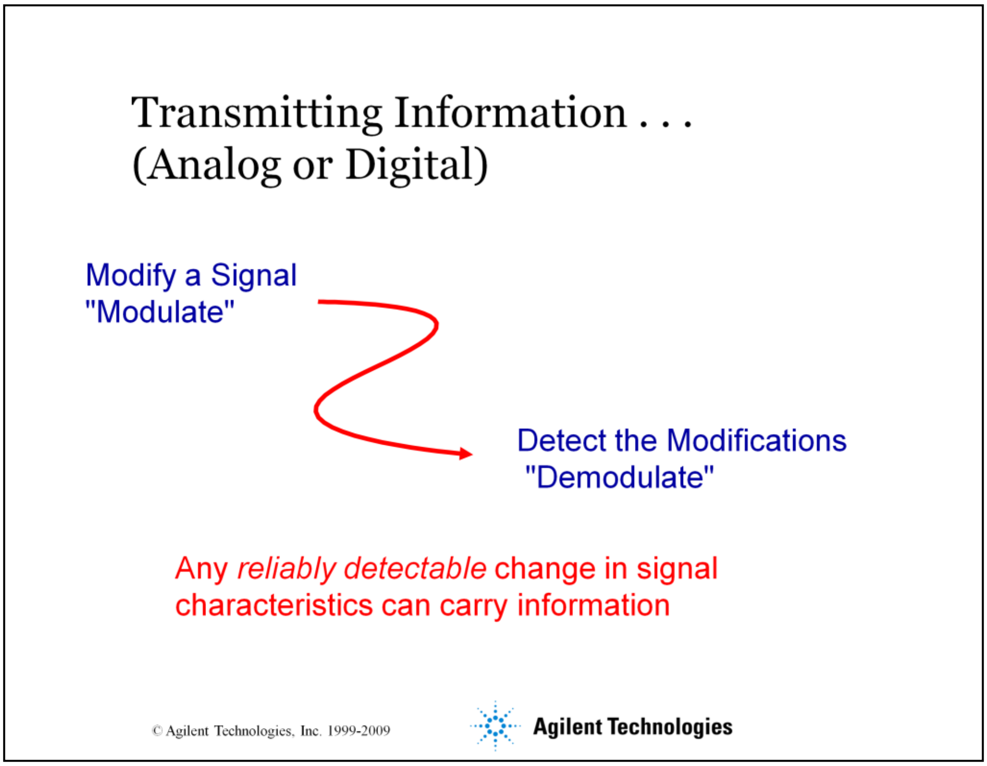
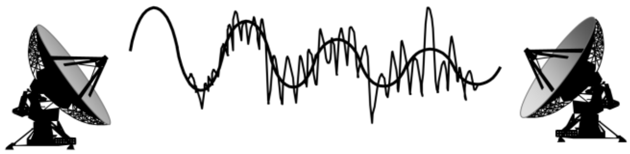


The message to be sent in any communications system must be modulated n to a carrier. Why? The carrier does just that: by using a high frequency (RF or microwave) as a carrier, the message will travel much farther than if you tried to send the baseband signal directly. [That's why you use the phone to call across town, rather than just shouting].

Analog vs. Digital Noise



As an analog signal is attenuated and noise is added, it becomes difficult to detect the signal accurately: remember every voltage value means something.

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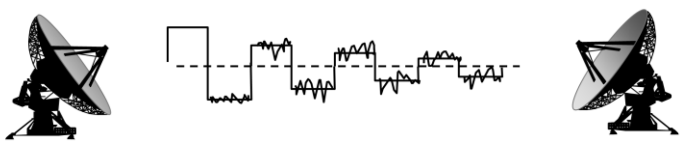
Here an analog signal is depicted with noise added to the signal. Notice that in this example, every voltage has a direct result at the output.

Digital Signals and Noise



As long as a digital signal doesn't acquire too much noise before detection, it can be accurately regenerated with no loss of information.

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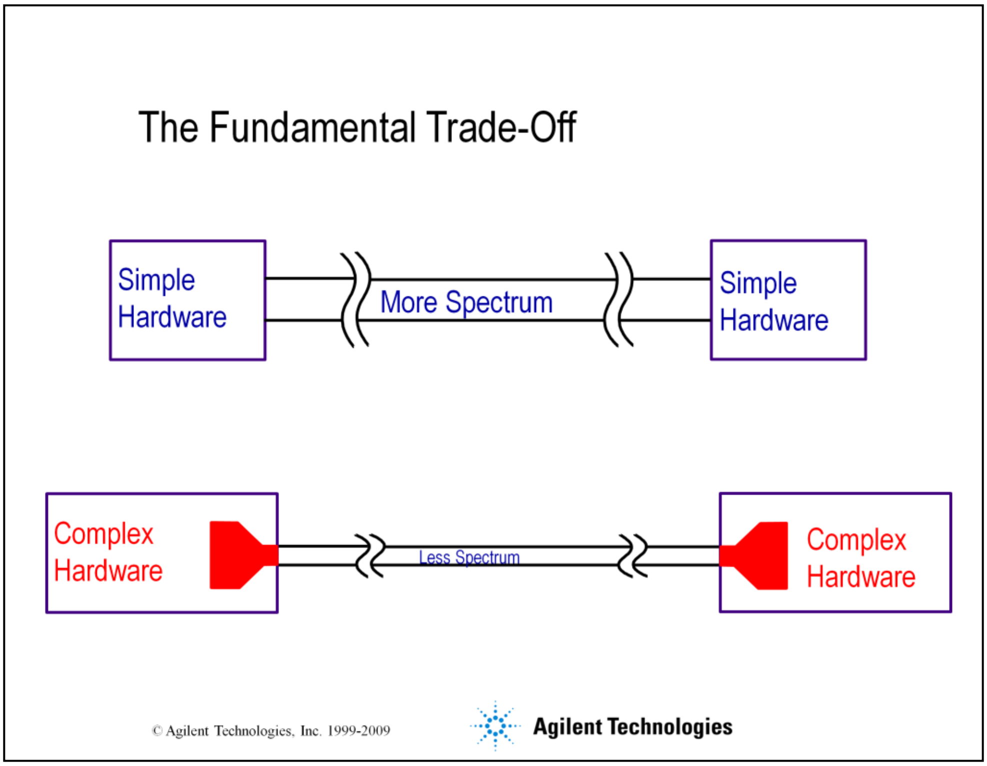
Shown is a digitally modulated representation. Notice that as long as the noise level isn’t too high, the receiver will detect the data properly.



This slide is a little deceiving: the complexity of IQ demodulator is really an illusion. The only ways of modulating a sinusoid is AM, PM or FM. IQ modulators just do this in a more general way. The more complex hardware really comes from requiring that the receiver know the phase and frequency of the carrier very precisely. This is known as coherent detection.

Simple Wave Equation

$$V(t) = A * \cos(2\pi f + \Phi)$$

What can we modify in this equation to
Change V(t) ???

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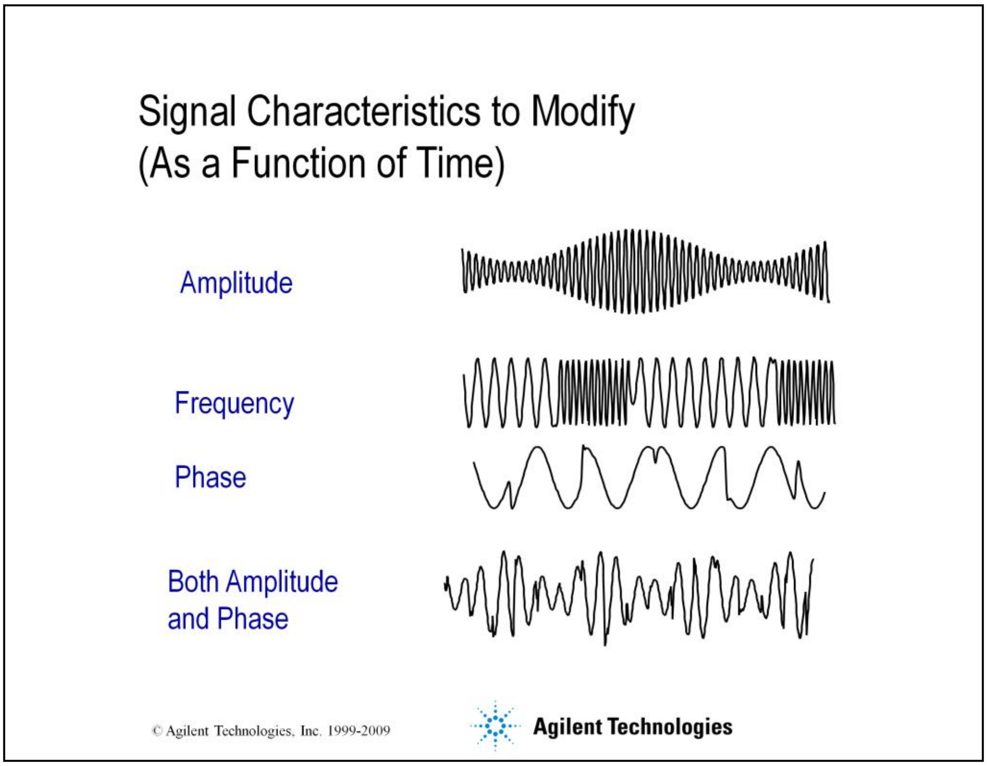
Think of modulation as modification of a signal in some way that can be reliably detected at the receiver.



The only difference between analog (old-fashioned) modulation and digital (new fangled) modulation is that a digital modulation restricts the modulating baseband signal to discrete states rather than allowing the modulating signal to take on any value between a maximum and a minimum value.

When AM, FM or PM are used in a digital modulation scheme, the names become ASK, FSK and PSK. The SK stand s for shift keying and is derived from an early form of digital modulation, Morse code.

IQ Modulation

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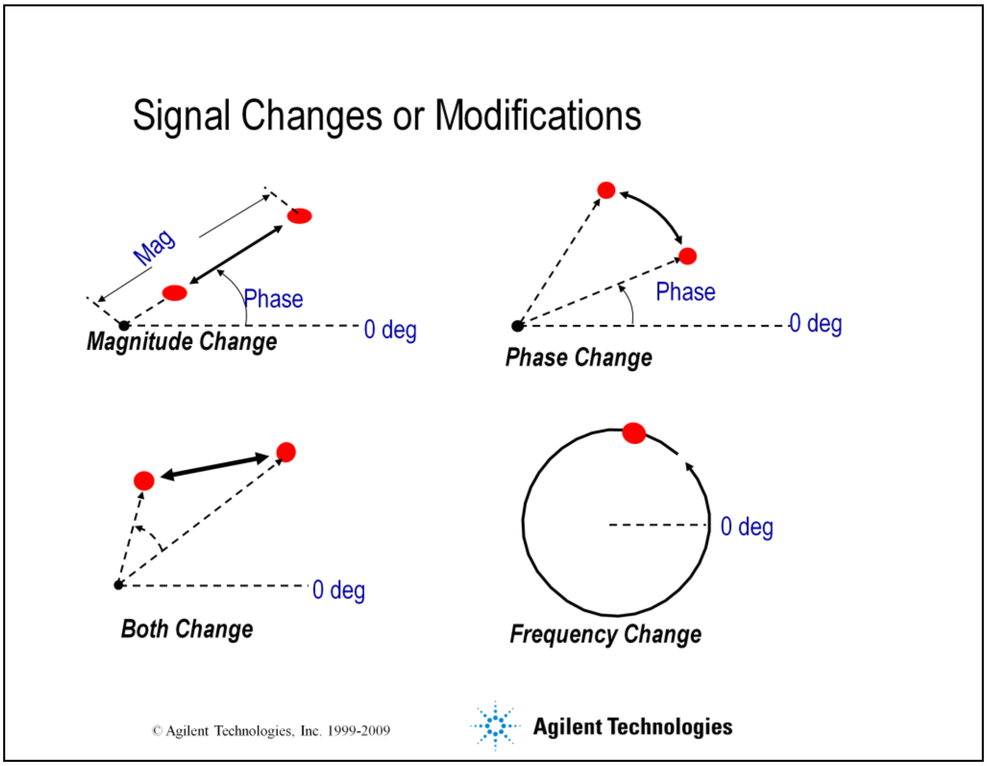
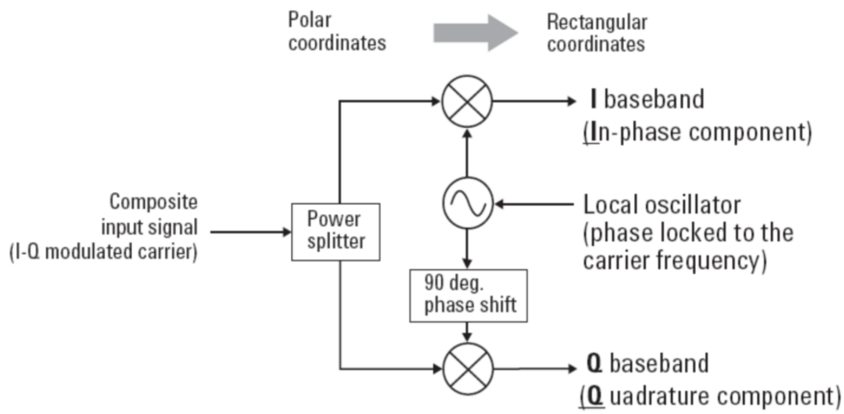


If you understand this slide, all I/Q modulation protocols are comprehensible.

On any I/Q diagram, if the signal moves toward or away from the origin radially, the power of the signal has changed. If a signal rotates around the I/Q diagram at a constant radius, the phase of the signal is changing (and only the phase). So AM would be a movement radially on an I/Q diagram, PM is a rotation around the I/Q plane. And FM will look like PM since a detected frequency different from the carrier frequency is really a change in phase per unit time.

Remember that amplitude and phase changes are always relative to the unmodulated carrier.

IQ Demodulation



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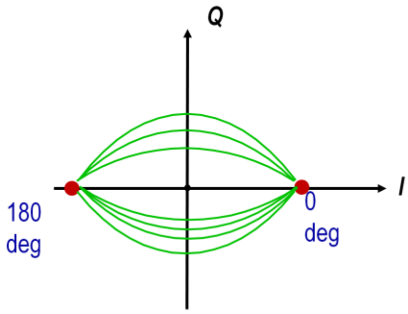
BPSK (continued)

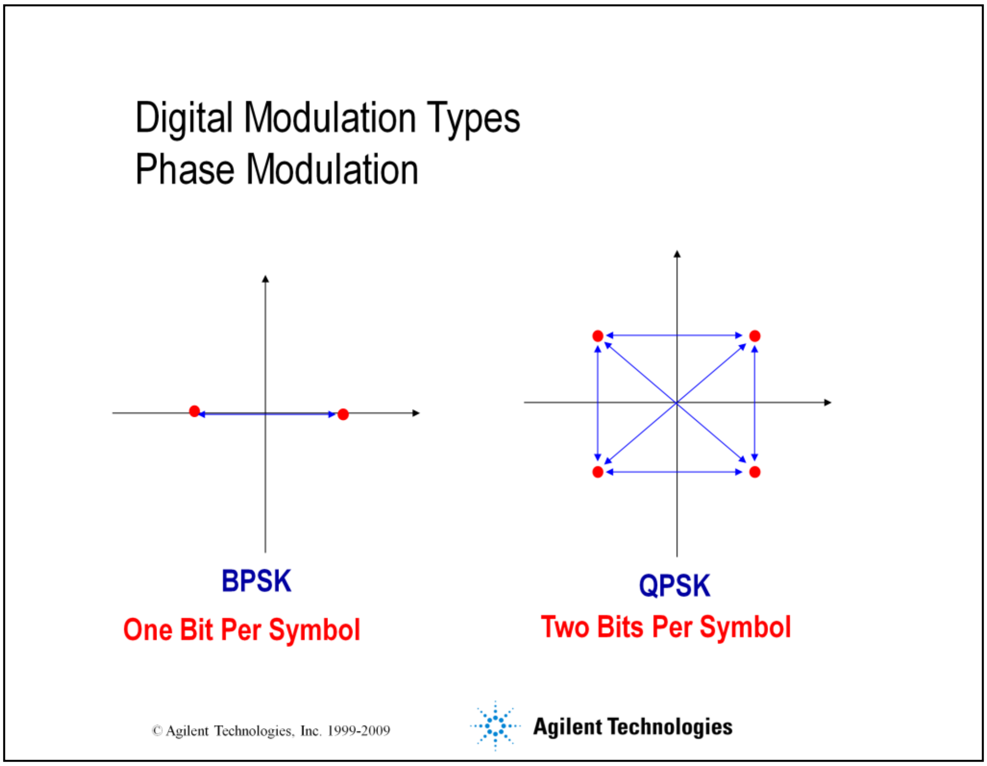


If the time signal of the sampled carrier is plotted on a polar diagram, this is what's displayed.

The set of expected sample points is called a constellation. If the transitions between sample points are shown, it's a vector diagram (greenlines).

The name BPSK arises from the fact that the data is transmitted via the two (and only two) possible phase states for the carrier (binary phase). (Does the amplitude of the carrier change??)

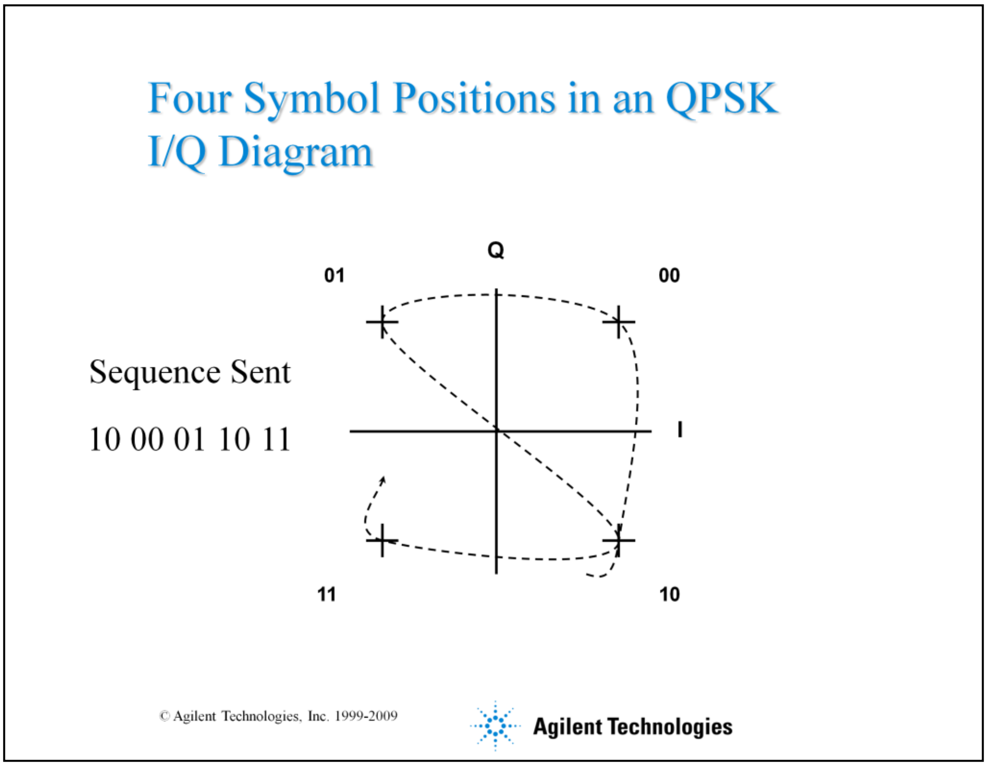
SHIFT KEYING comes from Morse code which was ASK, amplitude shift keying which means turning the amplitude on and off. Any time you see the phrase shift keying as part of a modulation protocol, you know it's digital modulation. The shift keying phrase implies that there are only a limited number of frequency (FSK), phase (PSK) or amplitude (ASK) states allowed which is consistent with digital modulation. In analog modulation, the change between phase, frequency or amplitude states is continuous.



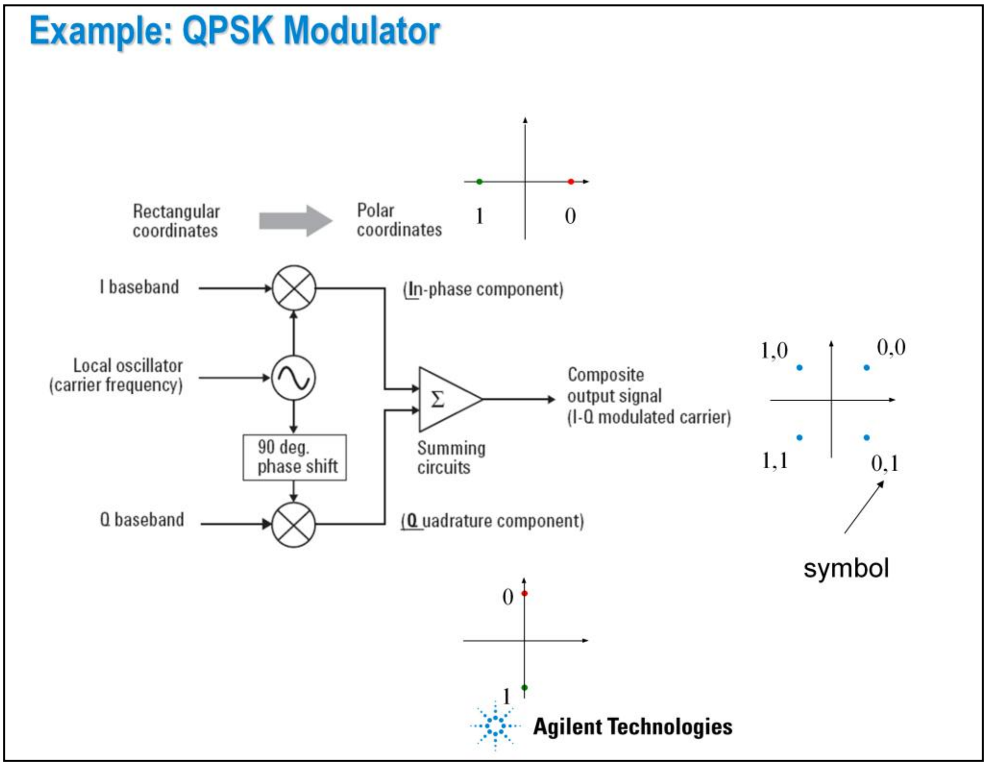
With BPSK, each phase state on the constellation diagram represents one bit, i.e., one bit per symbol.

What if four states were possible, not two. Now each phase state (symbol) can represent two bits.

Given the number of symbols (S) present on an IQ diagram, the number of bits/symbol (N) is log (base 2) of S.

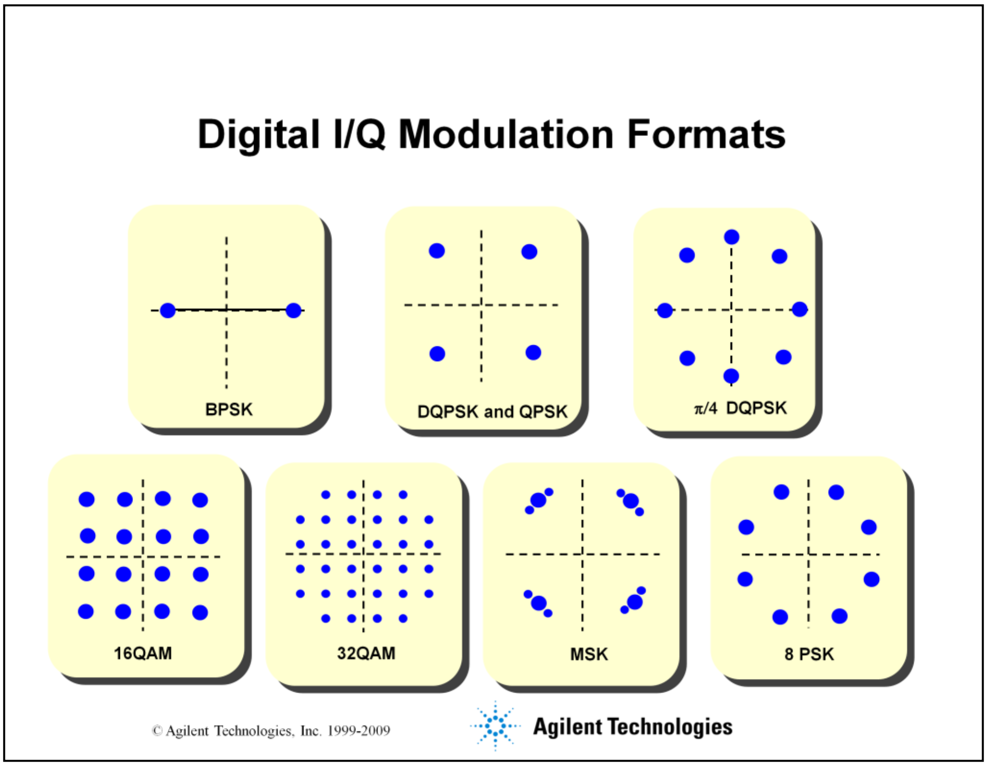


This slide shows an example of a set of 10 bits modulated onto a QPSK geometry. The arrow shows how the RF carrier is moving from state to state.



Here is an example of a Quadrature Phase Shift Keyed Modulator (QPSK) where two separate bit streams are independently modulated and then added together. This modulator works by adding the RF signals of two separate BPSK modulators with a 90 degree relative phase shift between them. The addition of the two modulated carriers provides the means to transmit two bits of information encoded into the output RF carrier. The two bits or “symbols” are still transmitted at the same rate as the input data streams thus making this form of modulation more spectrally efficient than BPSK modulation.

A symbol represents two or more bits.



Here are the I/Q modulation schemes typically found in the protocols shown on the previous slide. Please note that companies involved in manufacturing new communication systems investigate new and different I/Q modulation schemes all the time. Why these are some of the more common schemes will be explained as we go along.

Example of a Digital Bit Stream

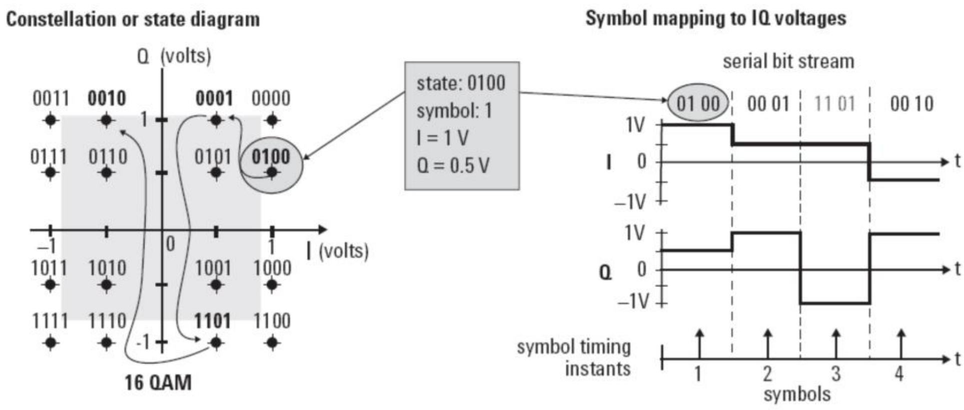


Figure 2-3. Each position, or state, in the constellation diagram represents a specific bit pattern (symbol) and symbol time

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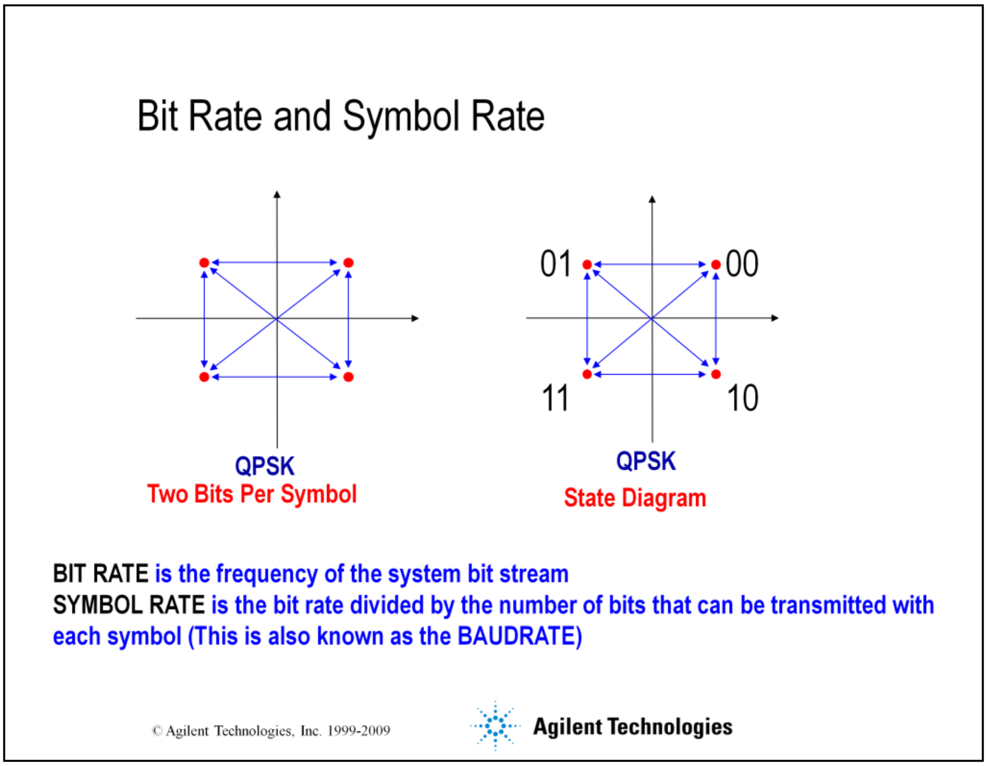
Here we see the transitions between symbol states as the bit changes in the two input data streams create instantaneous amplitude and phase transitions as the RF carrier is rapidly changed between symbol states. These instantaneous changes in the signal would require an infinite amount of signal bandwidth which is not practical in any wireless system due to limitations in the electronics and spectrum regulations determined by the FCC and other government agencies.



Why bother adding phase states? Didn't BPSK transmit the information just fine?

Consider the following situation. Assume you have a hardware system that can check the phase of a carrier every microsecond. If BPSK is used, the hardware will read 0, 180, 180, 0, 0, 180 for the phases of six transmitted symbols. This means the message was 1,0,0,1,1,0 and was transmitted in 6 microseconds (1 Mbit/s).

If QPSK were used, the detected phase might be 0, -45, -135 inthree microseconds. But now each phase state represents TWO bits and the transmitted message was 00, 10, 01, 10, six bits inthree microseconds (2 Mbits/s).

By using QPSK, you doubled the data rate transmission using the same sampling rate, the same hardware, the same bandwidth.

Major Modulation Goal:
Spectral Efficiency

Theoretical Bandwidth Efficiency Limits:

• BPSK	1 bit/second/Hz
• QPSK	2 bits/second/Hz
• 8PSK	3 bits/second/Hz
• 16QAM	4 bits/second/Hz
• 32 QAM	5 bits/second/Hz
• 64 QAM	6 bits/second/Hz
• 256 QAM	8 bits/second/Hz

Note: These figures CAN NOT be achieved in practical radios

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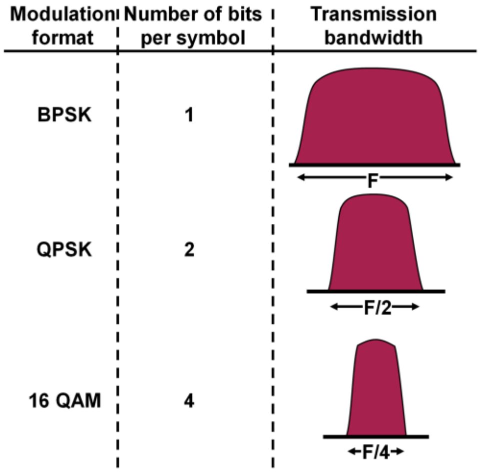
Having examined both BPSK and QPSK, you can now appreciate why most customers want to use the highest efficiency modulation format possible.

So why doesn't everyone use 256 QAM?   The answer is noise. For a given S/N ratio, the points on a dense constellation diagram will be closer together. If the noise environment of the transmitted signal is very bad (or there isn't a lot of signal available), high efficiency modulation schemes lead to high BER's.

If there's lot's of power available or the noise environment can be controlled, then high density modulation formats are used: phone lines, broadband digital and terrestial microwave transmissions.



digmod.fm
symbol1.wmf

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Filtering

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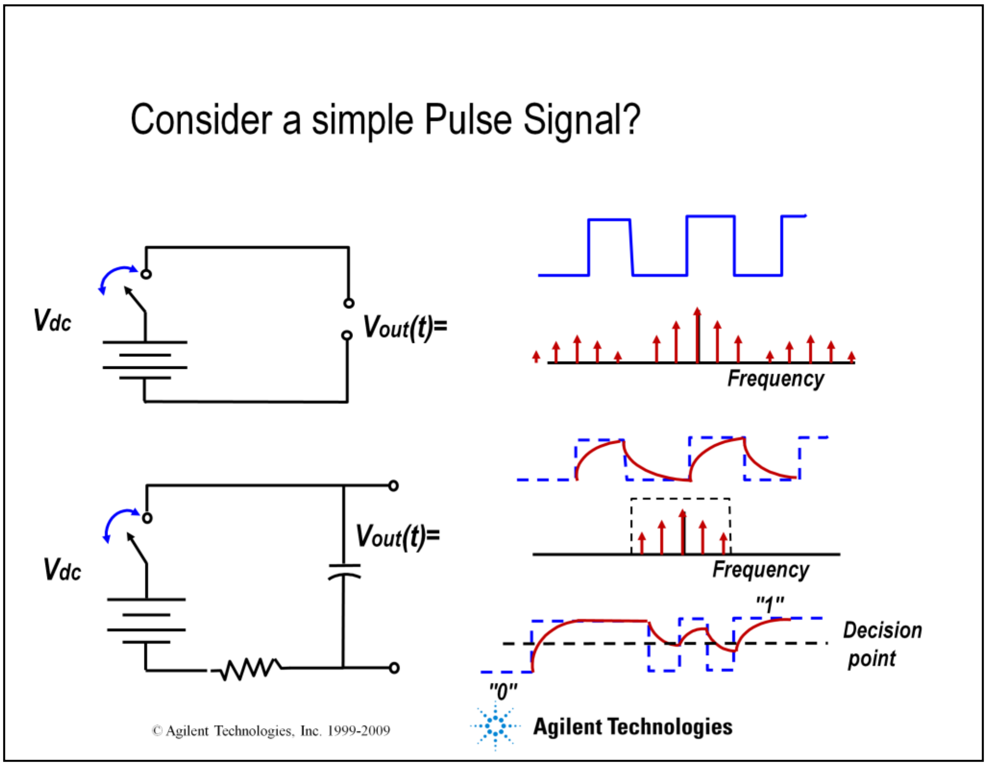
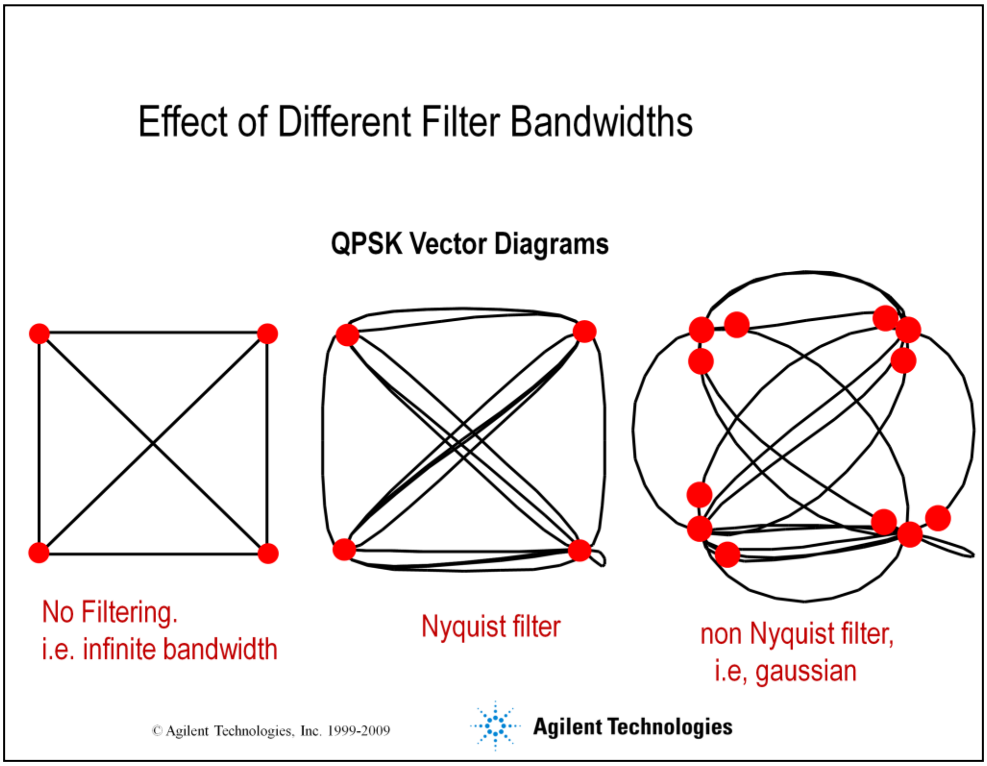


In addition to noise and distortion, the signal history of a system with finite bandwidth will also effect its ability to transmit bits correctly.

In the ideal case, a rapidly changing voltage can reach its final value in anarbitrarily short time. However, real signals are always time constrained in some way.

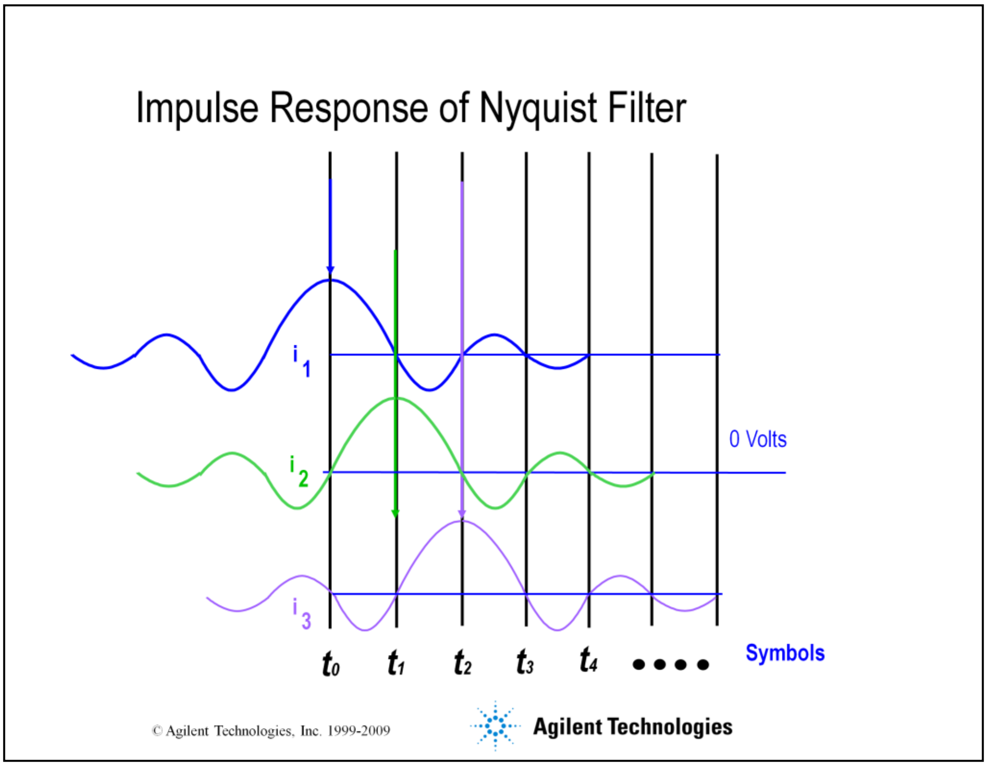
Consider a capacitive circuit charging and discharging. Depending on the time constant of this low pass filter, if the switch opens and closes too quickly, the output voltage may not achieve the final desired equilibrium value. If this were a digitally modulated carrier, if the time constants of the filter were too slow to respond to the rapidly changing bit stream, "incorrect" voltage values would be realized under certain conditions. This is aliasing.



Consider these practical examples.

The first I/Q diagram is using an infinite bandwidth filter. The transitions occur in a minimum time, but require infinite bandwidth. The second I/Q diagram is using a Nyquist filter, so the decision points haven't moved, but the path between points is different: instantaneous changes cannot occur.

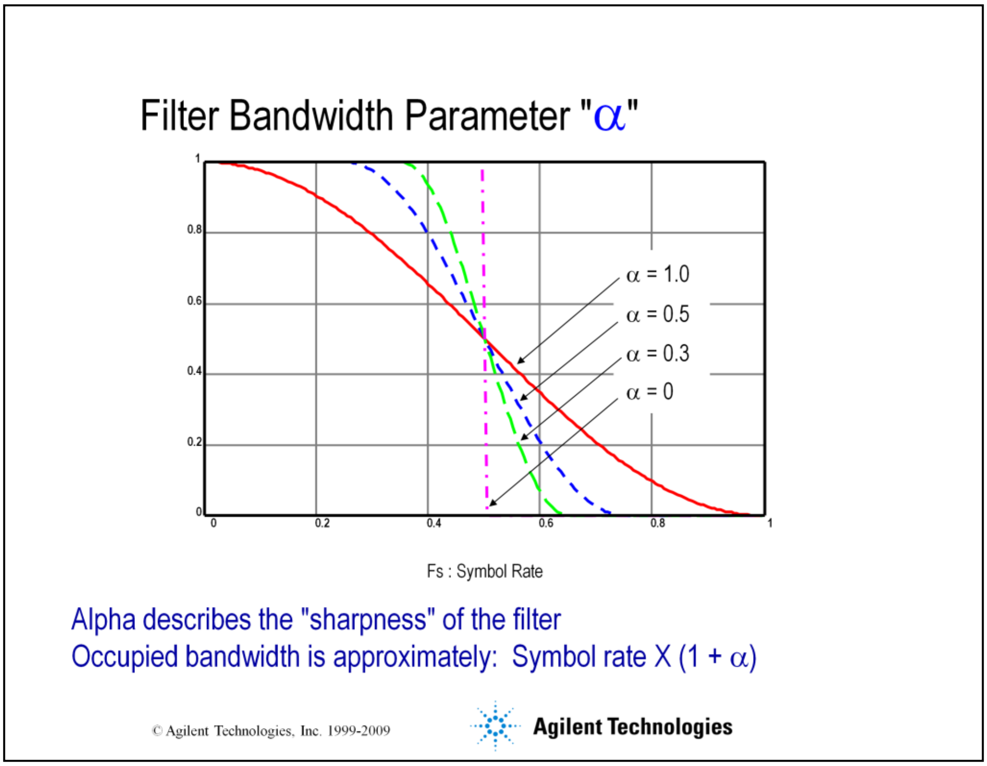
In the third example, a non Nyquist filter is used. Now the decision points may not occur exactly where they should (aliasing). Think of these as potential bit errors if the spreading of the decision points becomes too severe. The gaussian filter used in GSM, also known as GMSK, is a non Nyguist filter and this is why there are typically multiple points at the symbol locations (aliases). For GSM, the increase in aliasing is tolerated in order to achieve an bandwidth efficiency greater than possible with a Nyquist filter.



Since even band limited brick wall filters require an infinite number of poles (sections) and therefore cost any infinite number of dollars to build, Nyquist proposed the raised cosine filter which would have a finite number of elements, but required more than the minimum Nyquist bandwidth.

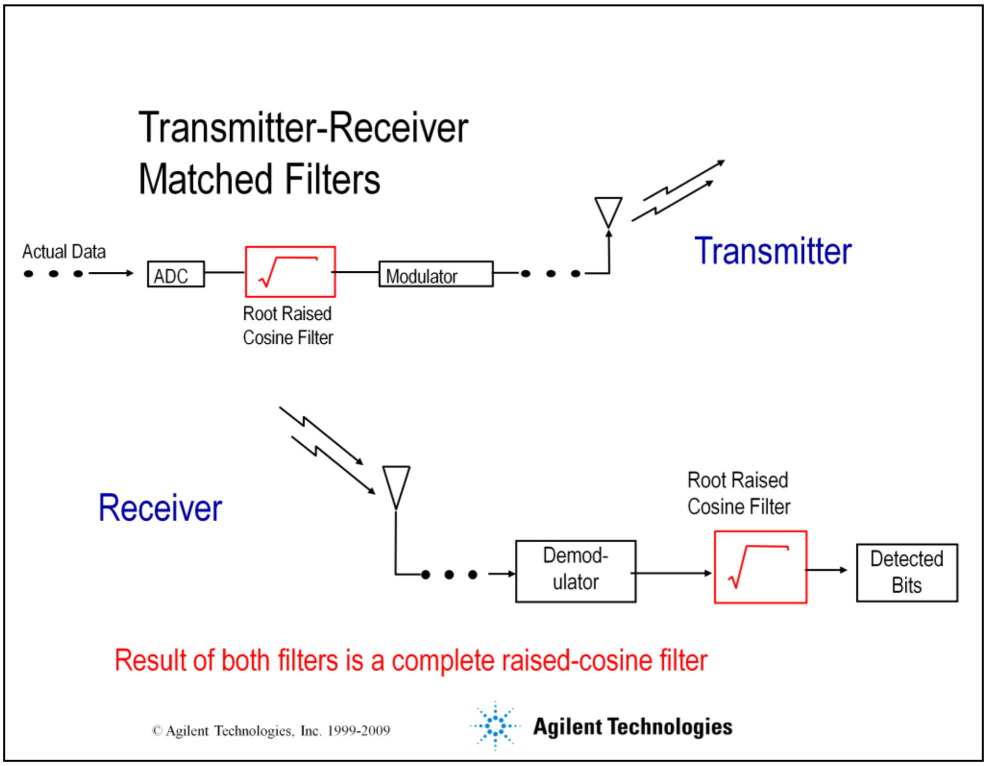
These filters work by canceling the hysteresis (memory) of previous transitions by having a time characteristic with an amplitude value of 0 at any sampling time other than the present one.

In the frequency domain, these filters assume a shape called a raised cosine.



The deviation from a "brick walled" shape in the Nyquist filter is called the alpha factor. The term 1+alpha represents the excess bandwidth over the minimum Nyquist bandwidth required to transmit the signal without ISI: intersymbol interference.

Even though the graph implies that the bandwidth is proportional to Fs/2, remember that the upconverted signal will occupy Fs bandwidth, hence the dependence of bandwidth on Fs, not Fs/2.



So what's a ROOT raised cosine filter?

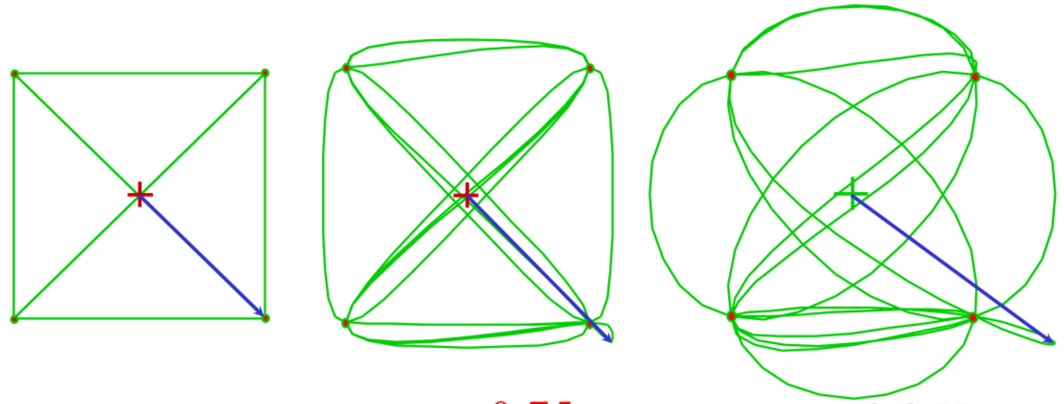
The Nyquist filter can be placed either in the transmit path to filter bits before transmission or in the receive path to filter bits after reception. The theory doesn't care. However, if the filter is place in the transmitter only, the receiver then operates "wide open". The noise floor in the receiver will be higher than if the receiver was band limited.

If the transmitter doesn't have filtering, the pulse nature of a digital signal will cause spectral spatter and potential interference with other users.

The compromise: put half the filter in the transmitter and half in the receiver. Since serial filter responses are multiplied in the frequency domain and the desired total filter response is a raised cosine, a root raised cosine is used in the transmitter and in the receiver.

Effect of Different Filter Bandwidths

- QPSK Vector Diagrams



No Filtering $\alpha = 0.75$ $\alpha = 0.375$

The effects of filtering can be seen in the Vector Display as well. No filtering results in a vector diagram with a neat square shape, but the tradeoff will be seen in the spectral display as excessive transmission bandwidth. As the alpha is reduced, the filter roll off becomes steeper, and the occupied bandwidth is reduced. However, notice that the ringing and slewing of the filter causes larger amplitude swings beyond the amplitude of a symbol transition. The vector from the origin to the lower right peak on the right hand graph shows the problem that the designer must allow more amplifier head room. This places a larger demand on the power amplifier to transmit the power peaks without saturation and distortion. The inter modulation distortion products show up in the adjacent channels, thus defeating the purpose of better filtering.

Digital Communications Measurements

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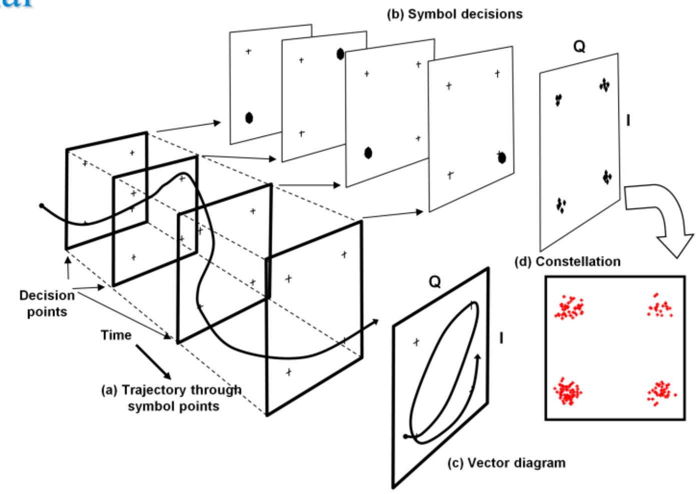
Vector & Constellation Diagram of a QPSK Signal



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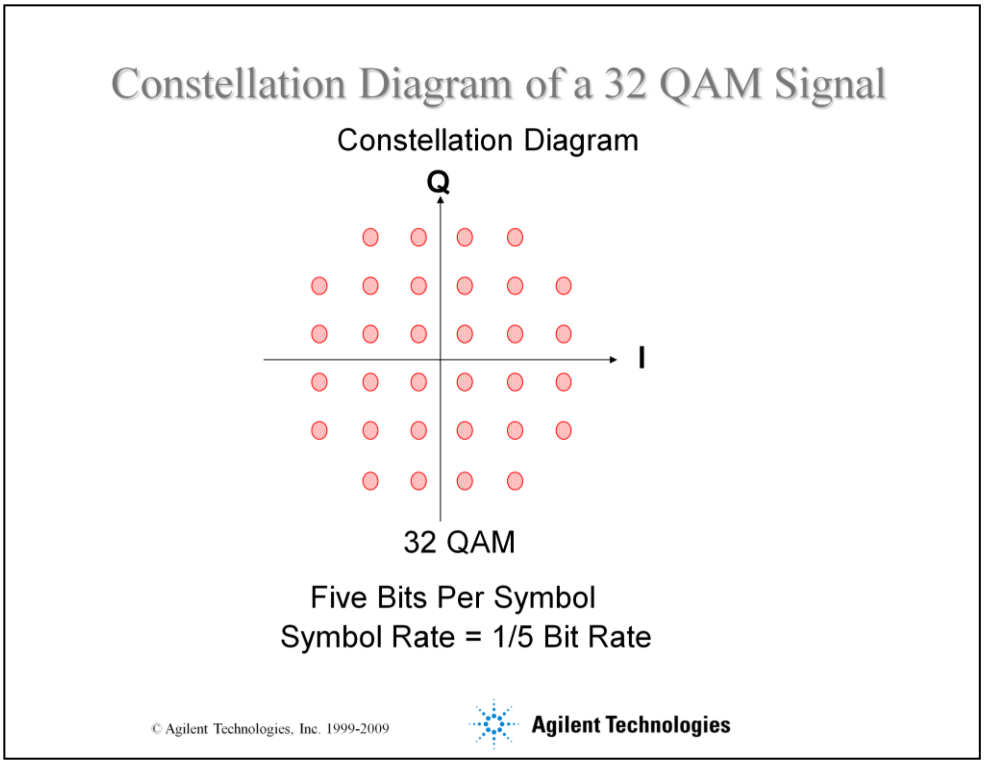
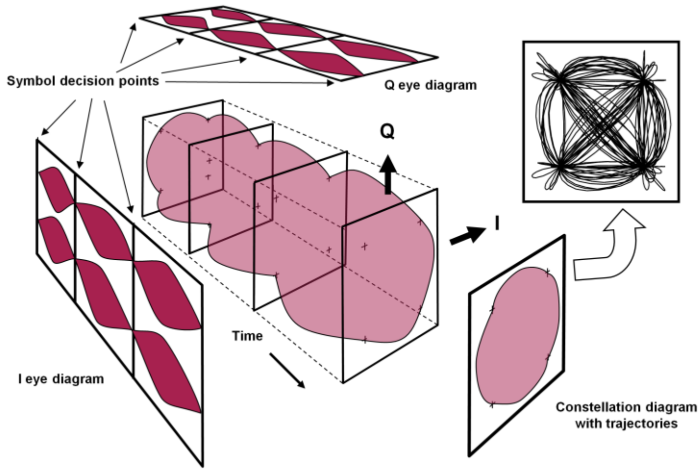


QAM is the typical modulation format used in Cable TV. This is a view of the signal as it is coming towards you. At the symbol times, how close is it to a particular state?

As the complexity of the modulation increases, the radio becomes more spectrally efficient. However, it also becomes more susceptible to errors caused by noise and distortion because the difference between adjacent states is smaller.

Eye Diagram of a QPSK Signal



Digmod.fm
IQ06.wmf

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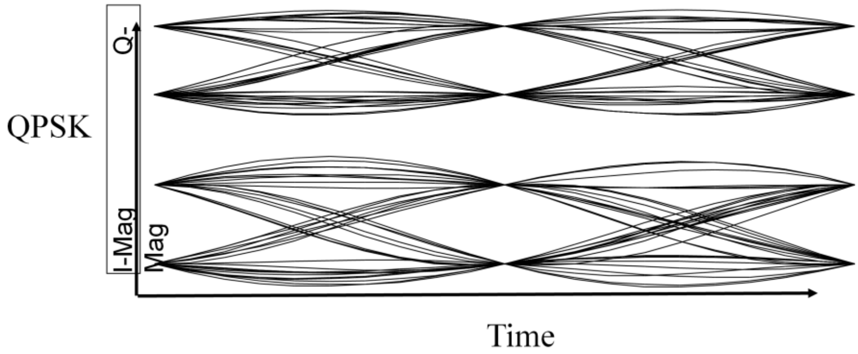
Eye Diagram of a QPSK Signal



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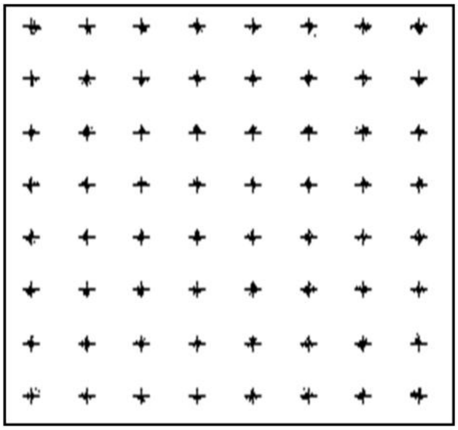
This is a view of the signal rotated 90 degrees and it is now going past us. The 'Eye" is the area between the symbol times near the symbol times. This is an ideal Eye. As noise or distortions make the states more uncertain, the Eye gets smaller.

Troubleshooting with Constellation Diagrams



A Clean 64 QAM Signal

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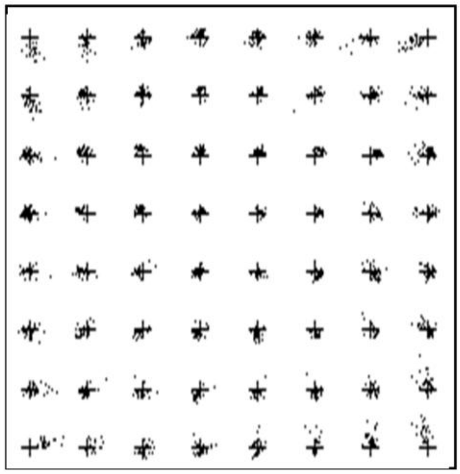
Shown is a high quality 64 QAM signal

64 QAM Constellation – Name the Impairment



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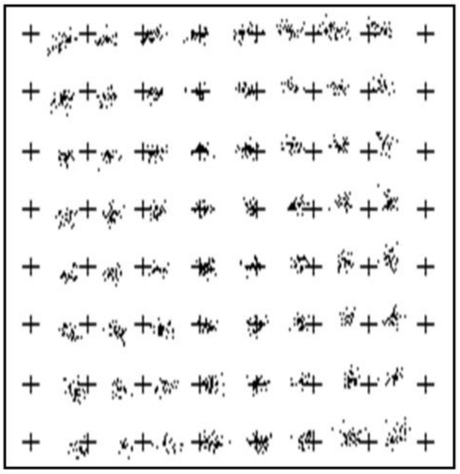
Notice the effects near the edge of the IQ plane. The system is having difficulty driving to the outer edges of the IQ plane which represents an amplifier entering compression.

64 QAM Constellation – Name the Impairment



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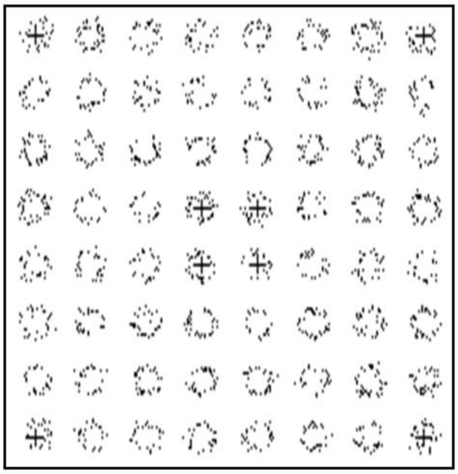
Notice the Q values are correct (rows) but the I values (columns) are incorrect. This is a gain imbalance between I and Q

64 QAM Constellation – Name the Impairment



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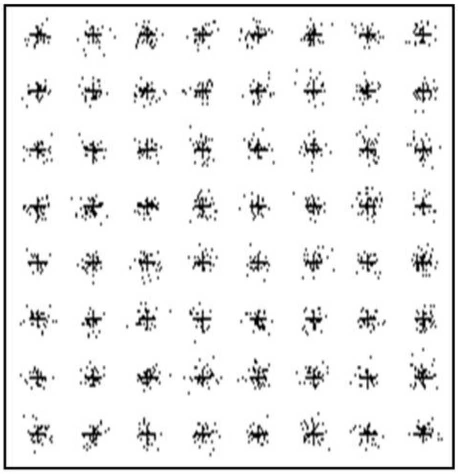
This is an interfering tone. The rotation speed of the circles represents the tone frequency that is interfering.

64 QAM Constellation – Name the Impairment



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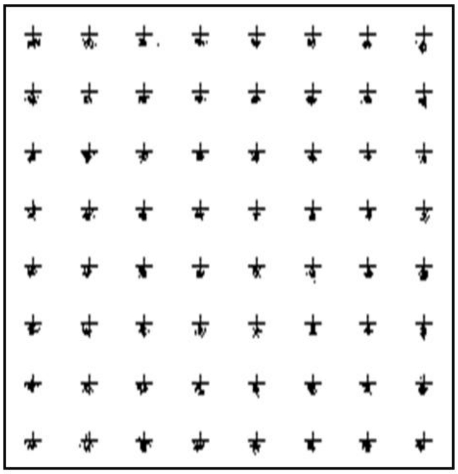
This is a degraded signal to noise signal.

64 QAM Constellation – Name the Impairment



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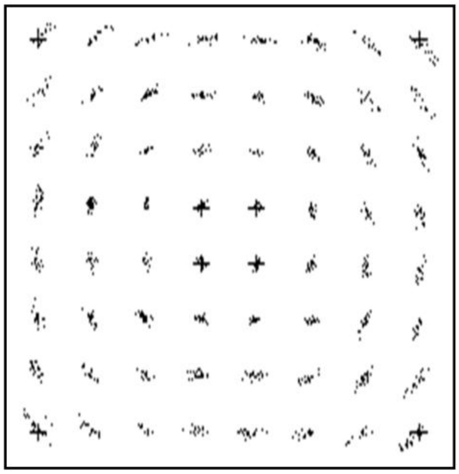
This has a 0 Hz or DC bias.

64 QAM Constellation – Name the Impairment



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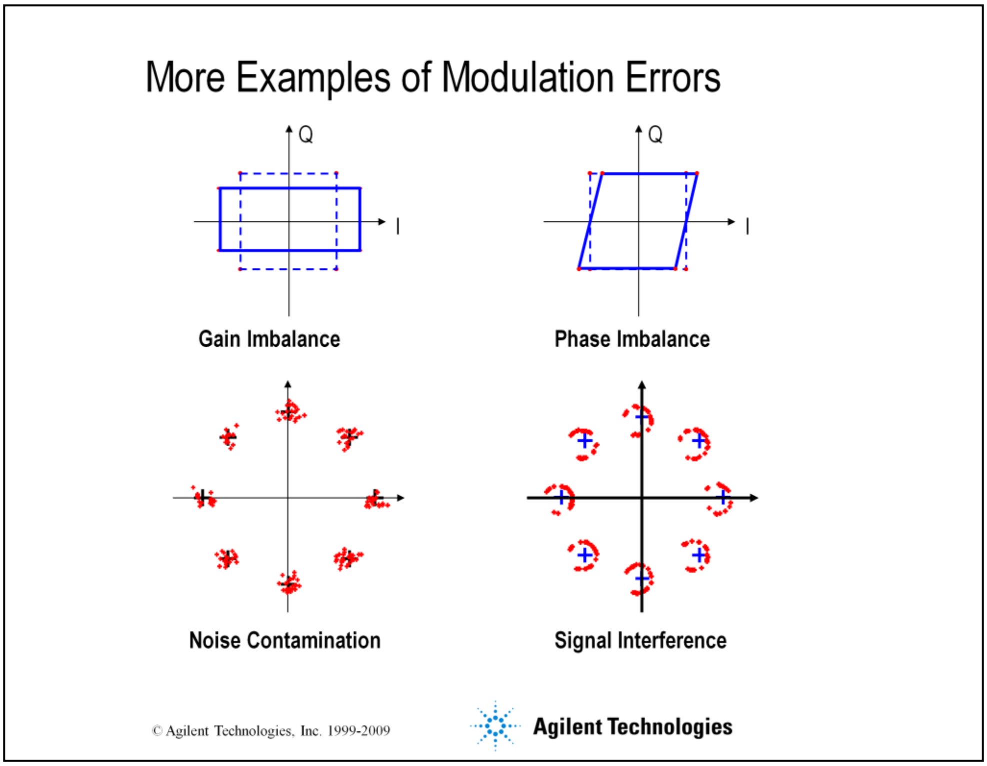
This is what phase noise looks like on a digital system.



Here are more typical IQ transmission impairments which can be quickly identified by the HP 894XX.

Quantitative IQ Measurements

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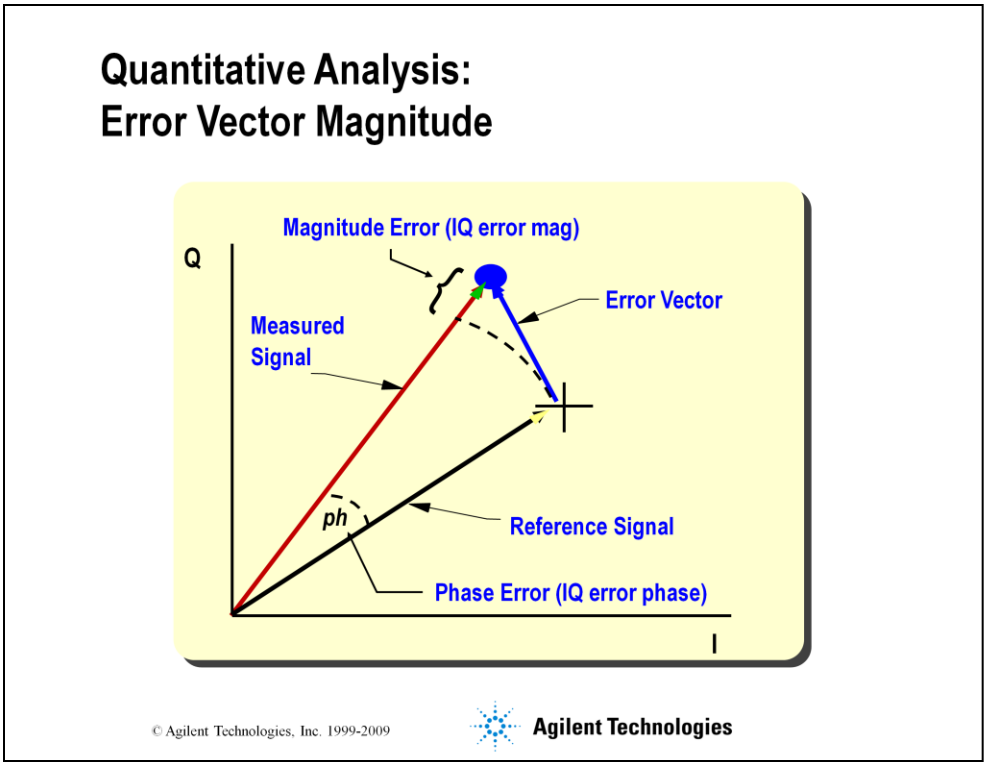

EVM provides a way to quantify the errors in digital modulation. The error vector is simply the difference between the actual constellation point and the reference or ideal constellation point. Note that we measure both magnitude and phase. Both are useful for evaluating problems.

The real value of EVM is estimating BER (bit error rate).

Calculating EVM, SNR

$$\text{Signal to Noise Ratio (SNR)} = -10 \log \left[\frac{(\text{average error magnitude})^2}{(\text{average symbol magnitude})^2} \right] \text{dB}$$

$$= \text{Modulation Error Ratio (MER)}$$

$$\text{Error Vector Magnitude (EVM)} = \frac{(\text{average error magnitude})}{(\text{maximum symbol magnitude})} \times 100\%$$

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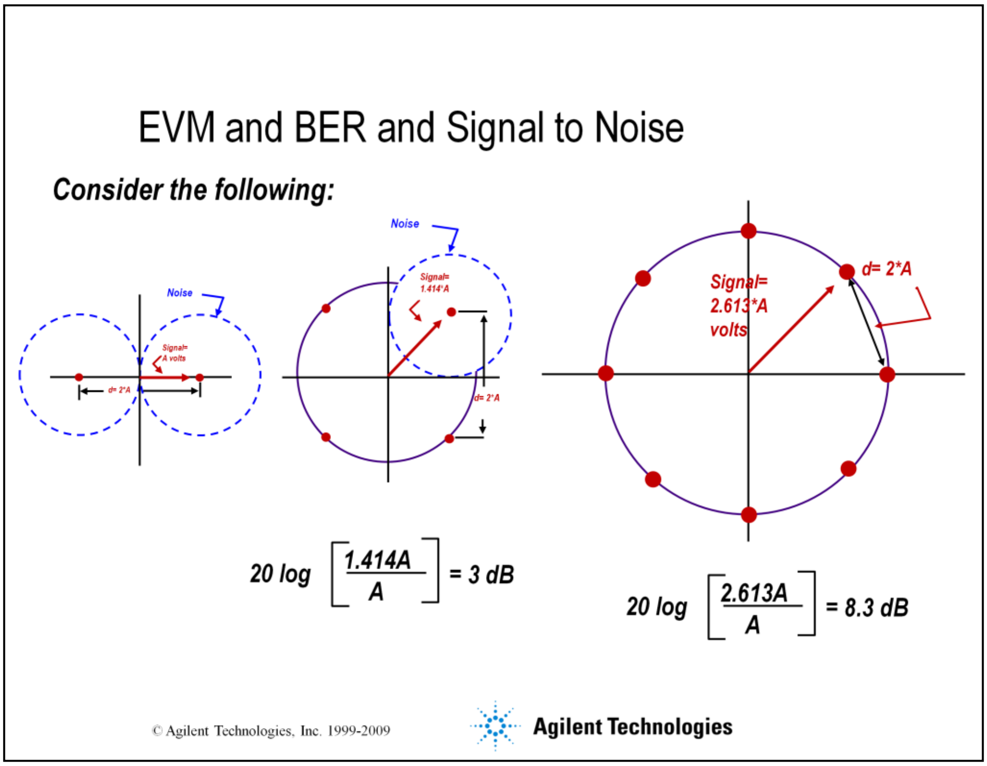
Here are the relationships which relate EVM to BER. BER is the ultimate measure of transmission quality: after all, we are talking about sending bits as the information.

Remember; if we're measuring symbol errors (MER), we're not quite measuring bit rate directly. But BER can be calculated from MER if you know the symbol mapping

Sometimes customers complain that the VSA family does not measure bit errors directly. Two comments should be made here. First, based on the way the VSA acquires data (sampling a time record), it's possible that an error could be missed (if the VSA is measuring data in a non-real time mode). Therefore, if you really want to look at BER not EVM, the HP 894XX may not be the instrument of choice. However, it should be noted, that if the BER to be determined is very low, measuring BER directly can be very time consuming (at a data rate of 10 kbits/sec, a 10^(-6) BR would require almost 17 minutes of test time). In this case, EVM may yield BER information more quickly.



The qualitative relationship between EVM and BER is shown here.

Consider a signal level of A volts for a BPSK signal. The nominal distance between the two decisions points is 2*A. The blue circle represents an arbitrary noise voltage which would begin to cause Bit errors to occur..

What signal strength is required for a QPSK signal to achieve the same BER in the presence of the same noise level? If we maintain the 2*A symbol location separation, the signal strength must be 1.414 V to achieve the same noise immunity. This is 3 dB higher than the BSPK signal.

The calculation for 8PSK relative to BPSK is also shown here.