QPSK and 16-QAM Digital Modulation

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Modulation

- Information such as sound (audio), images (video), and digital data can be transmitted from one point to another using radio waves
- This is done by modulating an RF signal—a carrier—with the information to be transmitted
- *Modulation* is the variation one or more properties of an RF signal to represent the information being transmitted

Modulation

- **One or more of the following properties of an RF signal may be varied to convey information:**

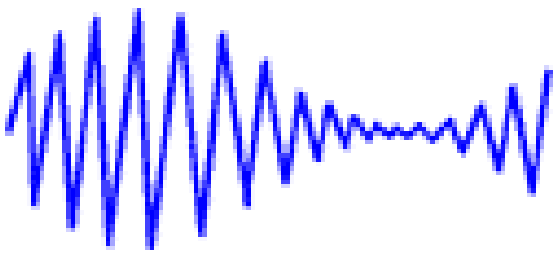
  ***Amplitude*—Amplitude of a carrier is varied. This is called amplitude modulation (AM).**

  ***Frequency*—Frequency of a carrier is varied. This is called frequency modulation (FM).**

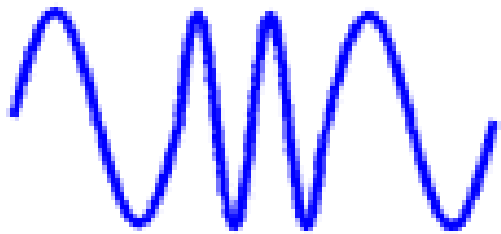
  ***Phase*—Phase of a carrier is varied. This is called phase modulation (PM).**

Modulation

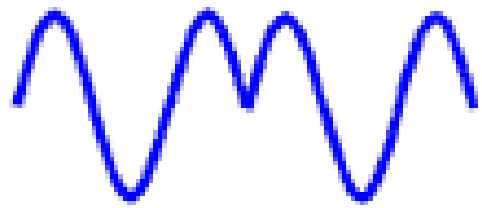
Here are three examples of commonly used modulation techniques, showing modulated signals in the time domain. In these examples the horizontal axis is time, and the vertical axis is amplitude.



AM: amplitude modulation



FM: frequency modulation



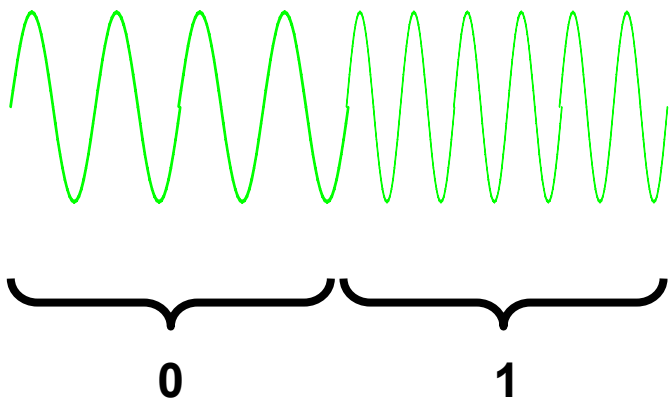
PM: phase modulation

Modulation

A radio receiver—TV set, AM or FM radio, and even a cable modem or CMTS—detects an RF signal's variations, and creates a nearly identical copy of the original modulating signal from those variations.

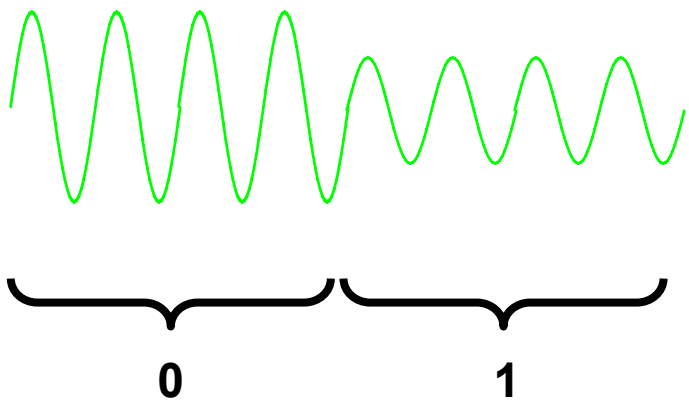
Basic Digital Modulation Formats

- **FSK—Frequency shift keying: Information is transmitted by shifting between two frequencies to represent zeroes and ones**



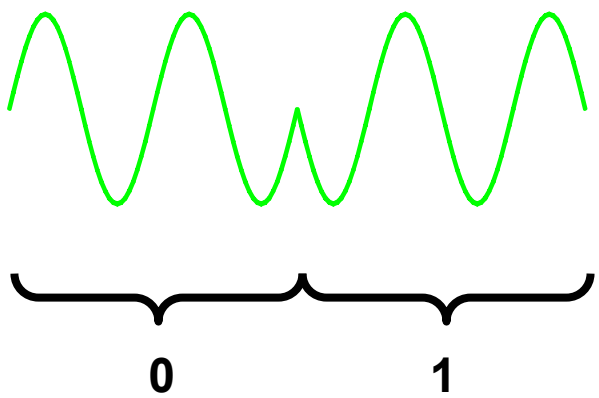
Basic Digital Modulation Formats

- **ASK—Amplitude shift keying: The amplitude of a carrier is shifted between two states to represent zeroes and ones**



Basic Digital Modulation Formats

- **PSK—Phase shift keying: The phase of a carrier is varied between two states to represent zeroes and ones**
  - **If the phase shift between the two states is 180 degrees, the modulation is called BPSK, or biphase shift keying**

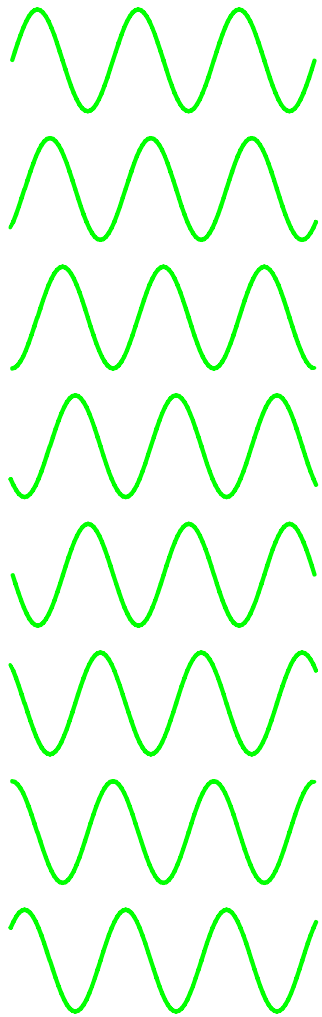


More About Carrier Phase

- These graphics represent RF carriers in the time domain with different phases relative to one another. They all have the same frequency and the same amplitude.

- Assume that the top carrier is assigned an arbitrary phase value of 0°

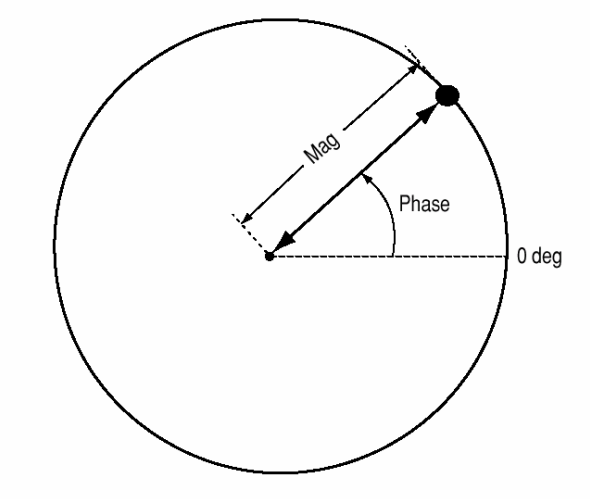
- The second carrier's phase relative to the first one is delayed 45°, the third carrier is delayed 90°, the fourth carrier 135° and so on



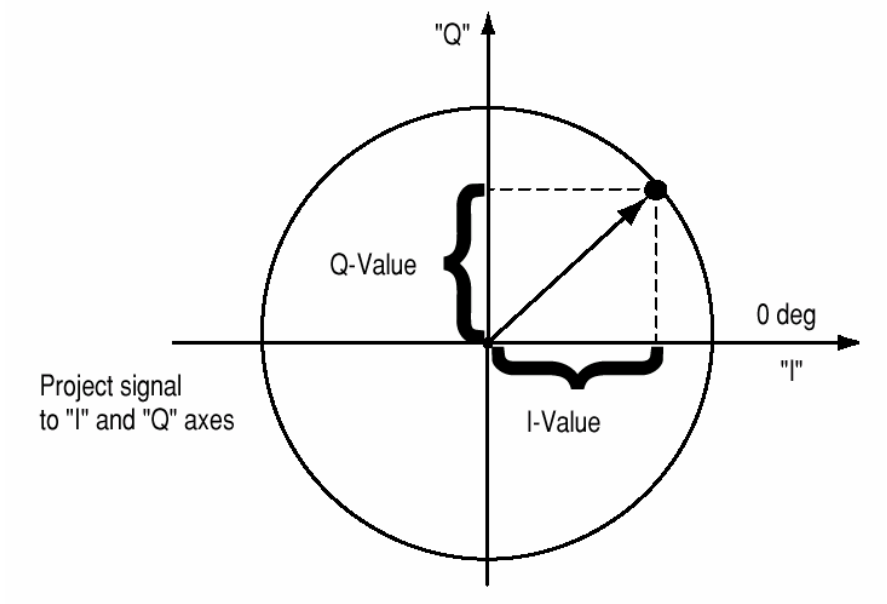
I/Q Modulation

- Amplitude and phase can be modulated simultaneously and separately to convey more information than either method alone, but is difficult to do
- An easier way is to separate the original signal into a set of independent components or channels: I (In-phase) and Q (Quadrature)
- The I and Q components are considered *orthogonal* or *in quadrature* because they are separated by 90 degrees
- The I and Q components are summed in a modulator circuit

I/Q Modulation



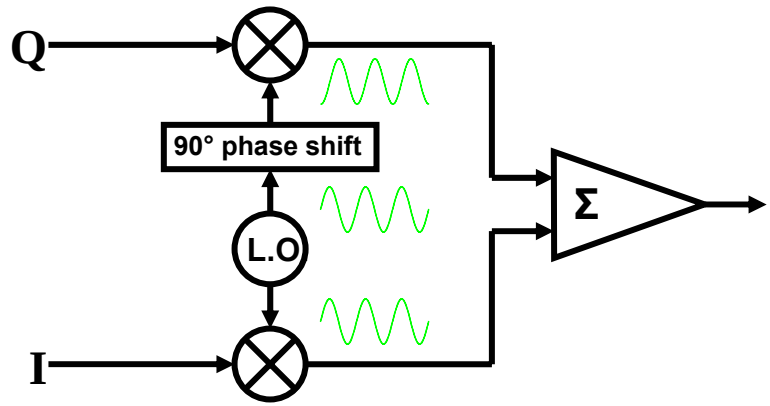
Polar display—Magnitude and phase represented together



“I-Q” format—Polar to rectangular conversion

I/Q Modulator

- A single carrier generated by a local oscillator (L.O.) circuit is split into two paths
- One path is delayed by an amount of time equal to ¼ of the carrier's cycle time, or 90 degrees
- The two carriers are amplitude modulated—one by the I signal, the other by the Q signal
- The two modulated carriers are added together in a summing circuit
- The output is a digitally modulated signal whose amplitude and phase are determined by the amplitudes of the two modulating signals



QPSK

- QPSK: quadrature phase shift keying
- *Quadrature* means the signal shifts among phase states that are separated by 90 degrees
- The signal shifts in increments of 90 degrees from 45° to 135°, -45° (315°), or -135° (225°)
- Data into the modulator is separated into two channels called I and Q
- Two bits are transmitted simultaneously, one per channel

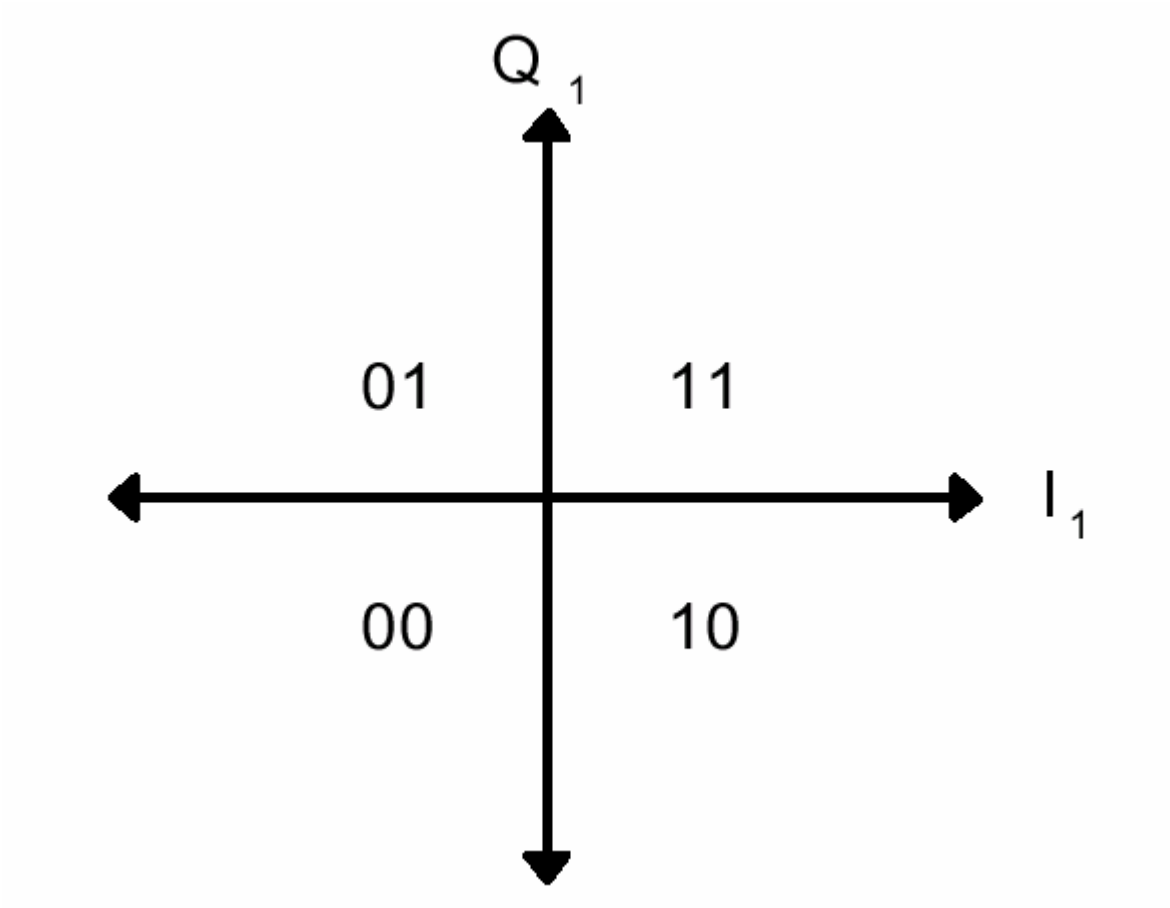
QPSK

- **Each channel modulates a carrier**

  The two carrier frequencies are the same, but their phase is offset by 90 degrees (that is, they are “in quadrature”)

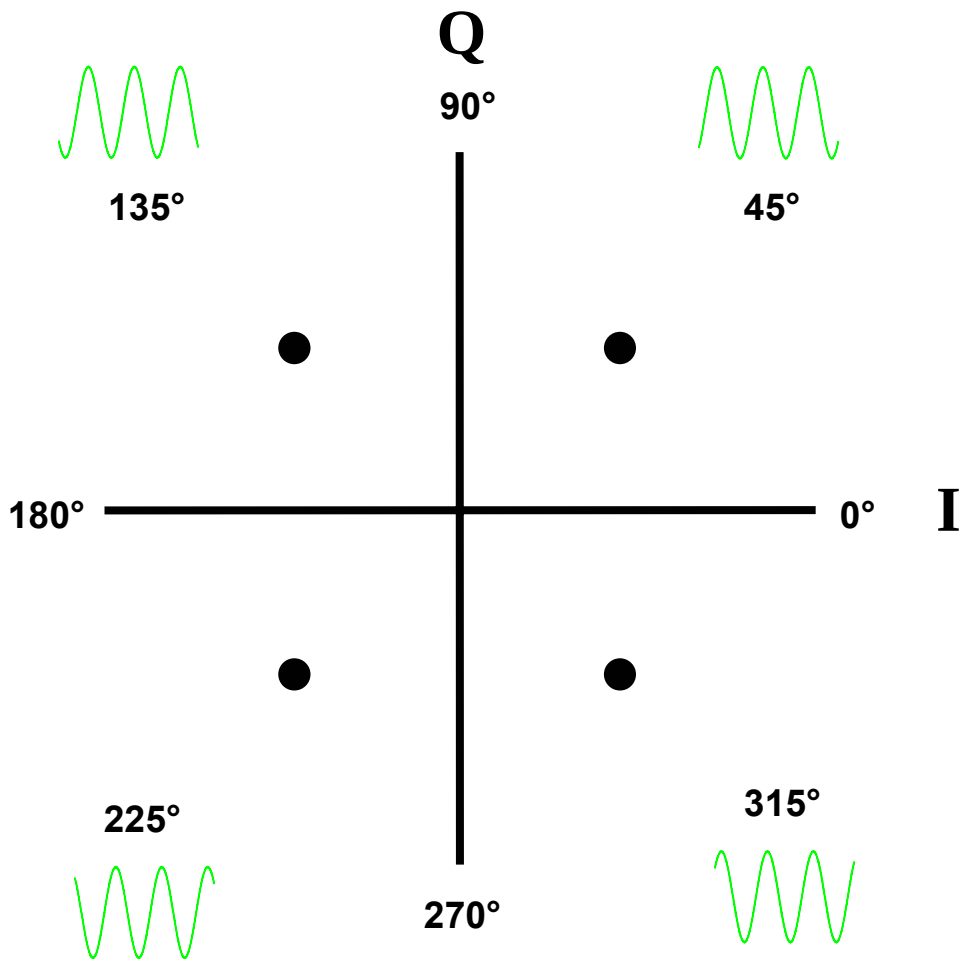
- **The two carriers are combined and transmitted**
- **Four states because $2^2 = 4$**
- **Theoretical bandwidth efficiency is two bits/second/Hz**

QPSK Symbol Mapping



QPSK Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
00	225°	1.0
01	135°	1.0
10	315°	1.0
11	45°	1.0



QPSK Constellation

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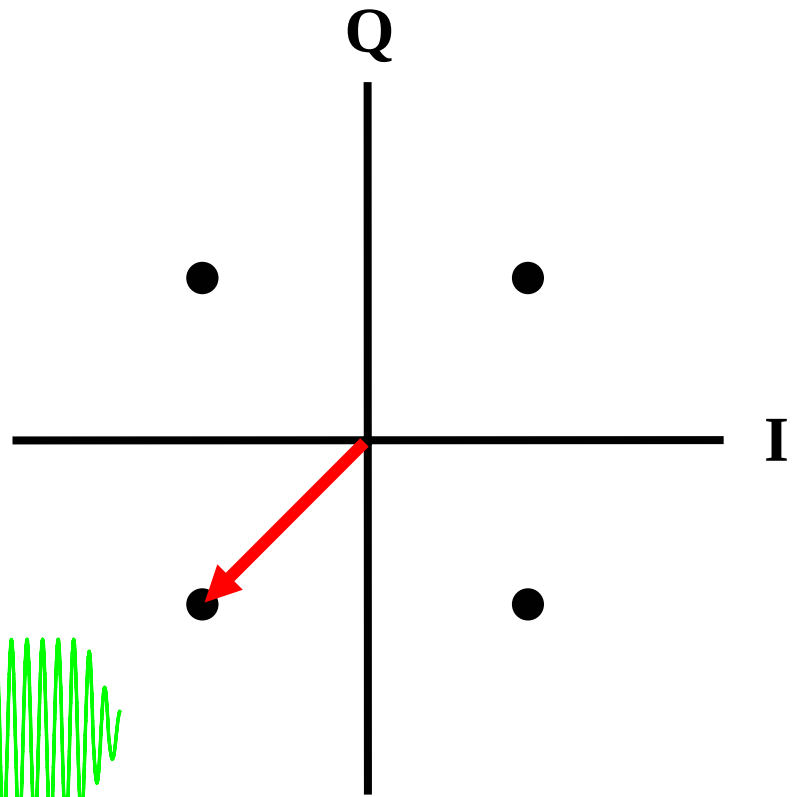

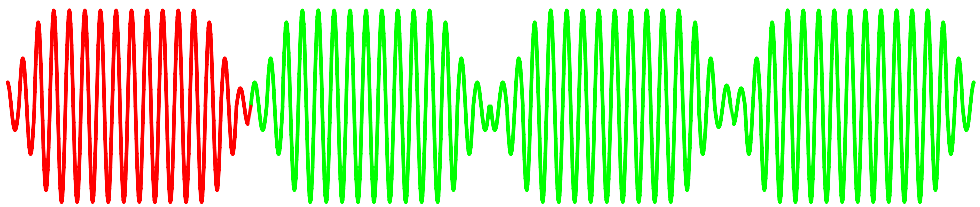

QPSK Constellation

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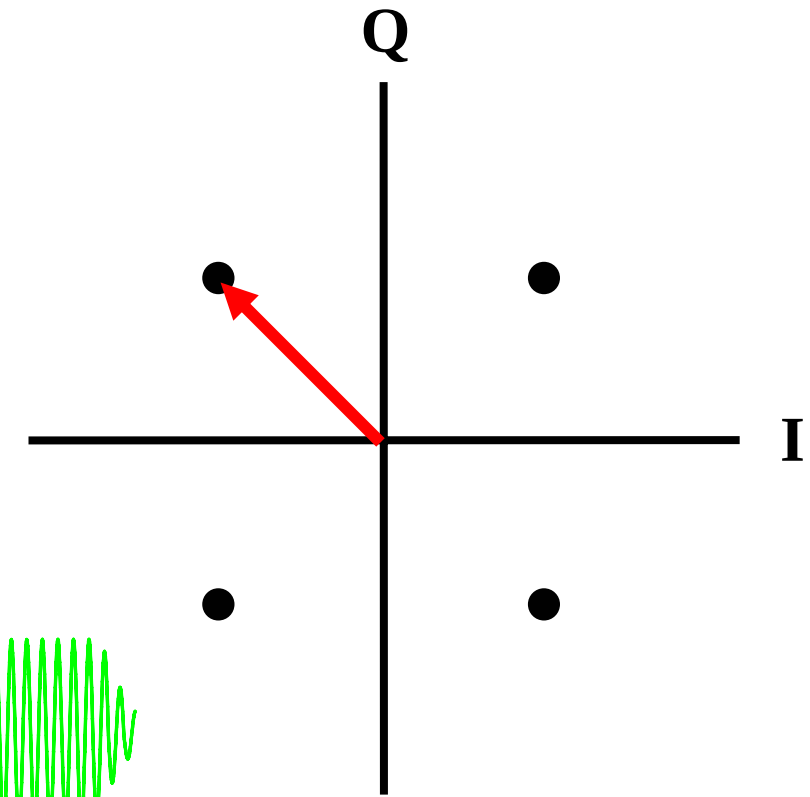

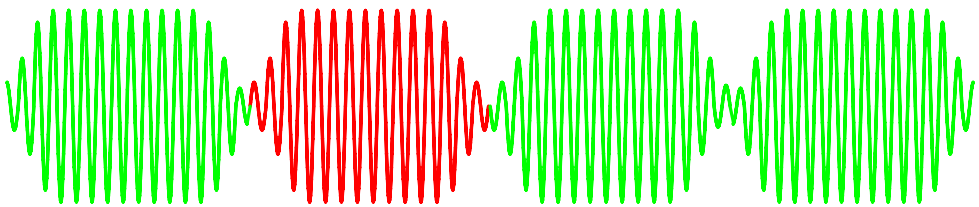

QPSK Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
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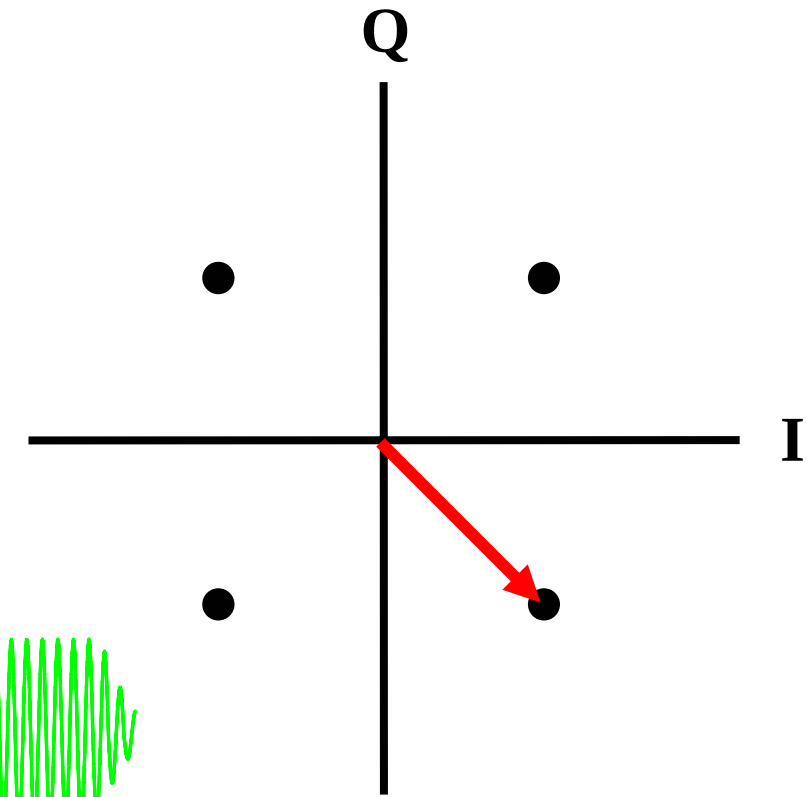
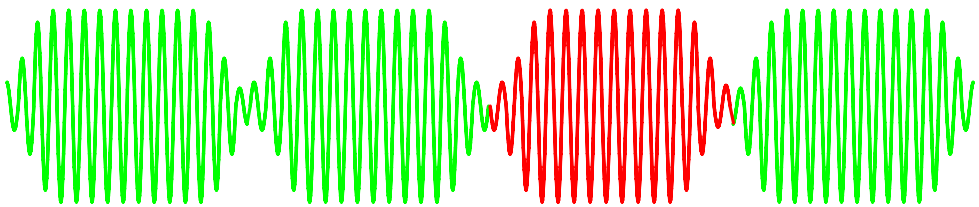
01	135°	1.0
10	**315°**	**1.0**
11	45°	1.0





QPSK Constellation

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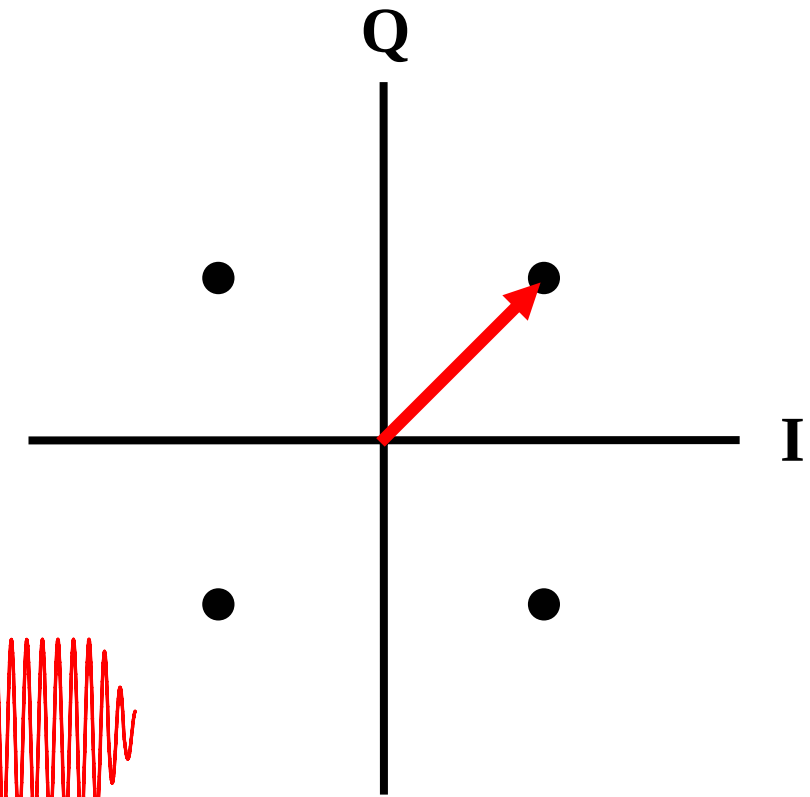
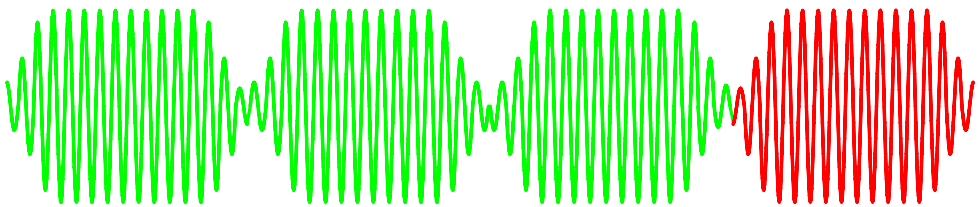
01	135°	1.0
10	315°	1.0
11	**45°**	**1.0**





16-QAM

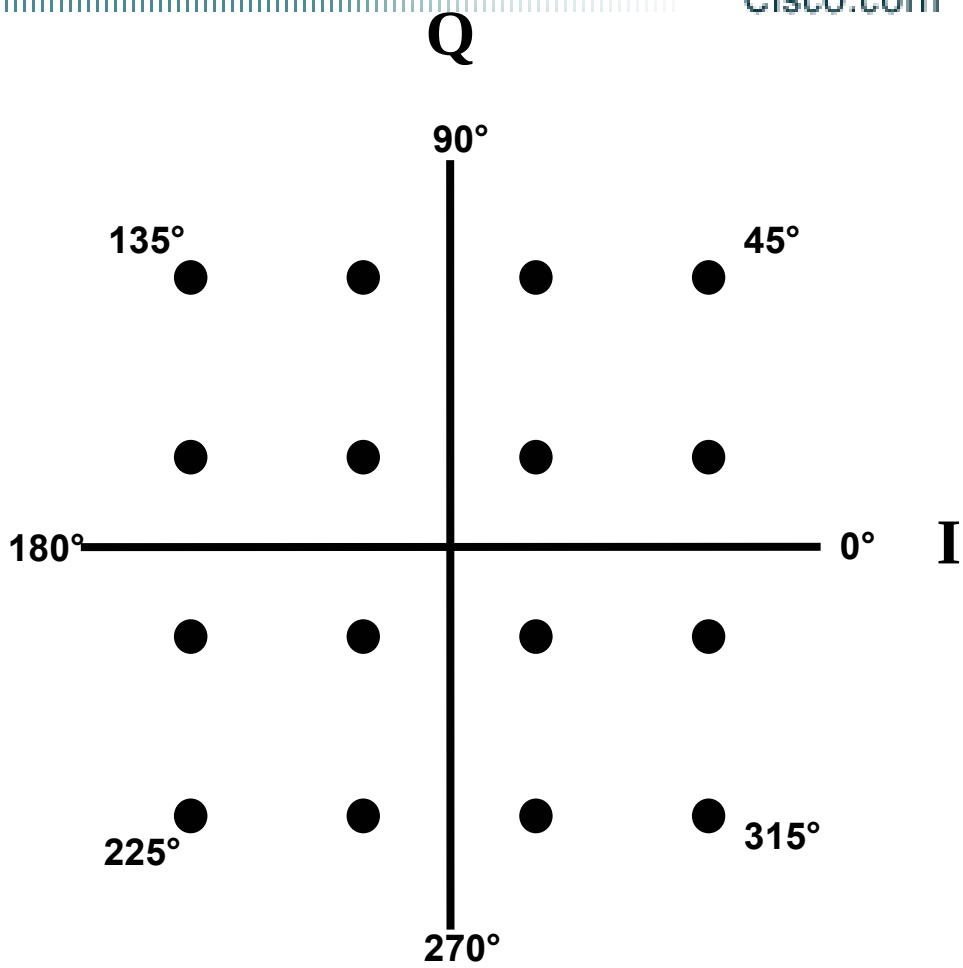
- 16-QAM: 16-state quadrature amplitude modulation
- Four I values and four Q values are used, yielding four bits per symbol
- 16 states because $2^4 = 16$
- Theoretical bandwidth efficiency is four bits/second/Hz

16-QAM

- Data is spit into two channels, I and Q
- As with QPSK, each channel can take on two phases. However, 16-QAM also accommodates two intermediate amplitude values!
- Two bits are routed to each channel simultaneously
- The two bits to each channel are added, then applied to the respective channel's modulator

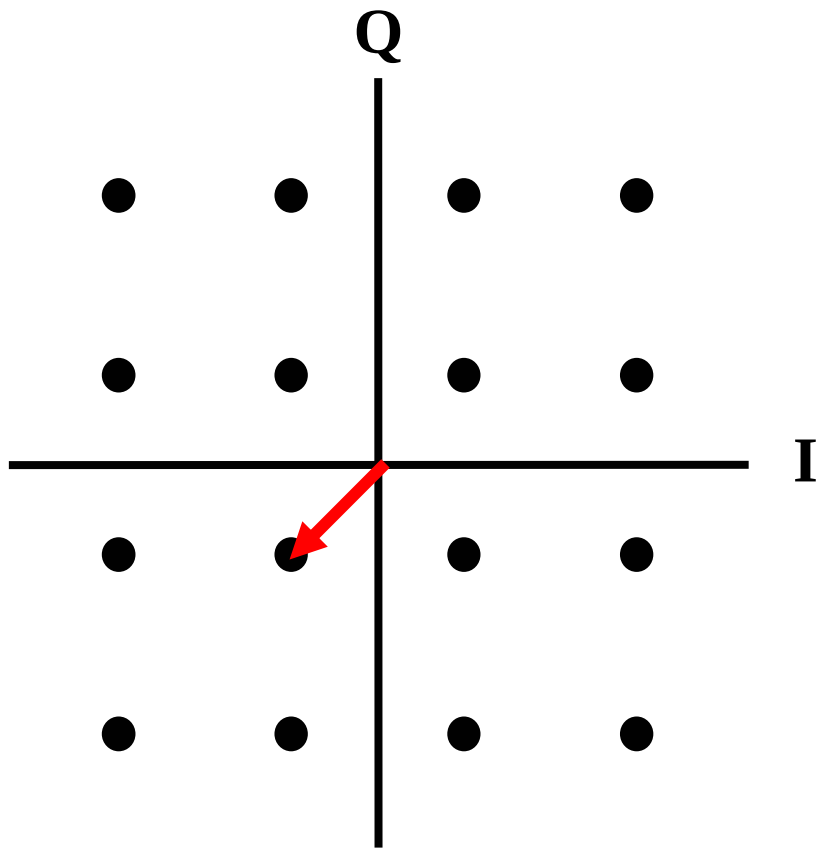
16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



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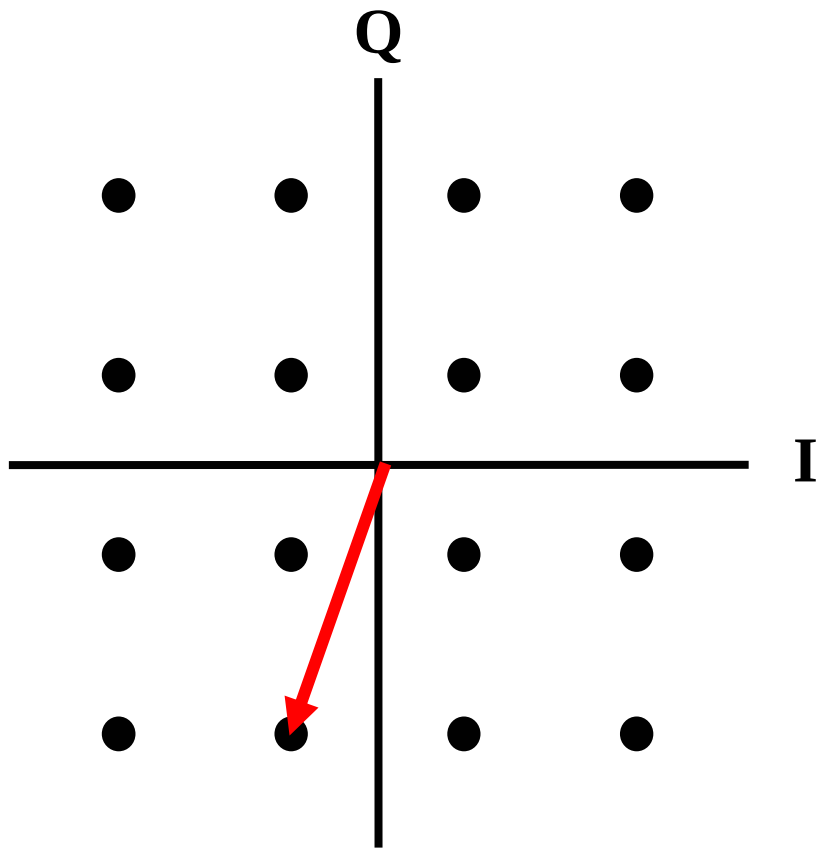
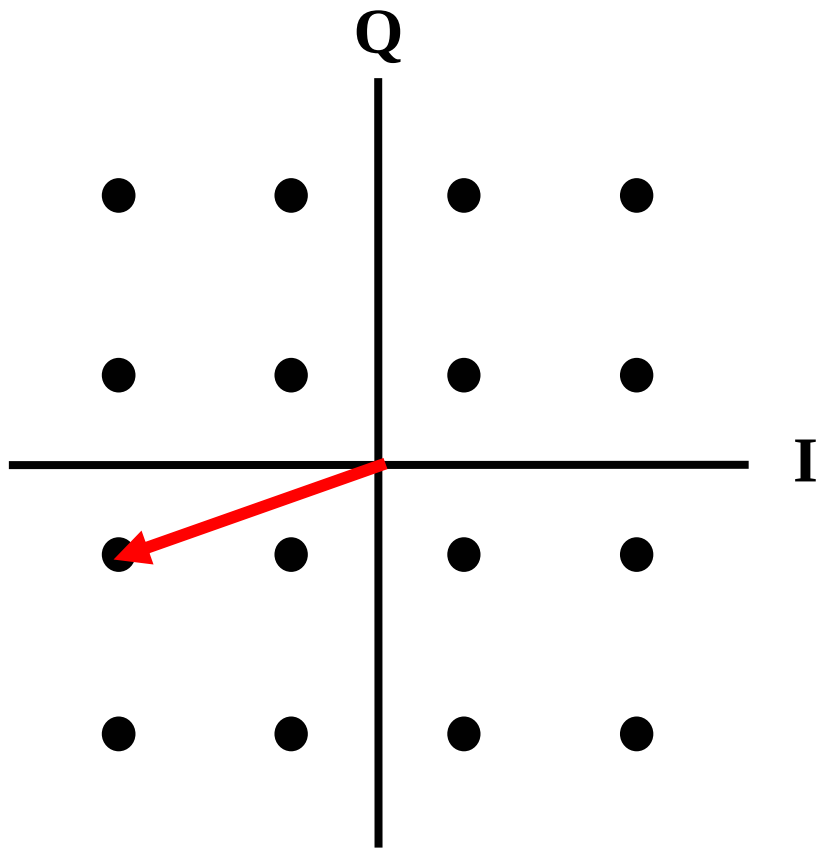
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	**195°**	**0.75**
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



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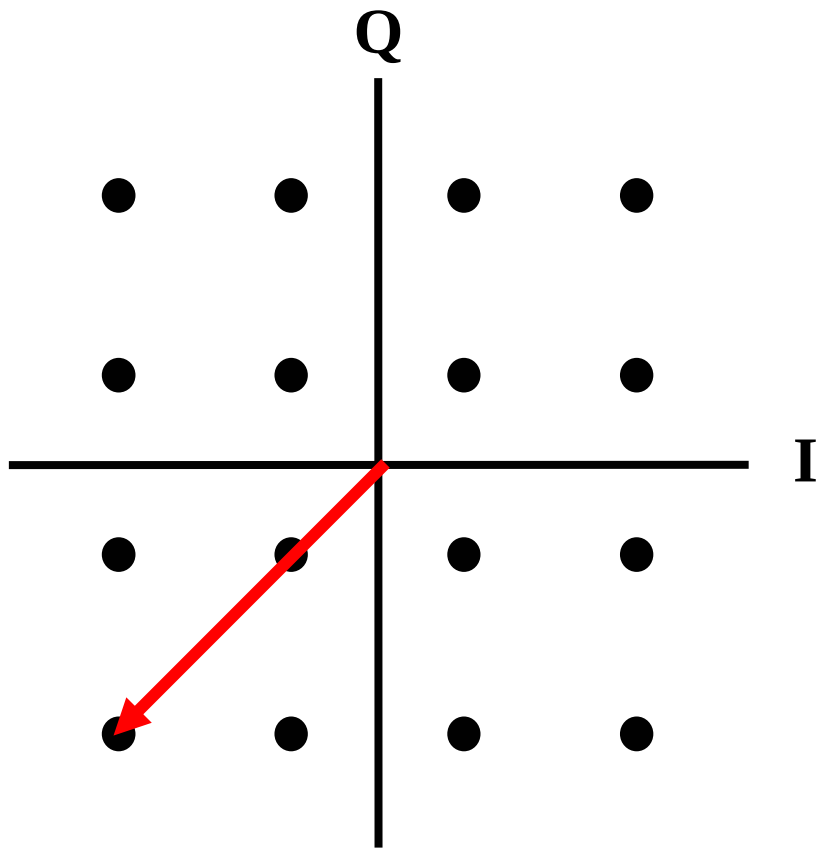
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	**225°**	**1.0**
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



16-QAM Constellation

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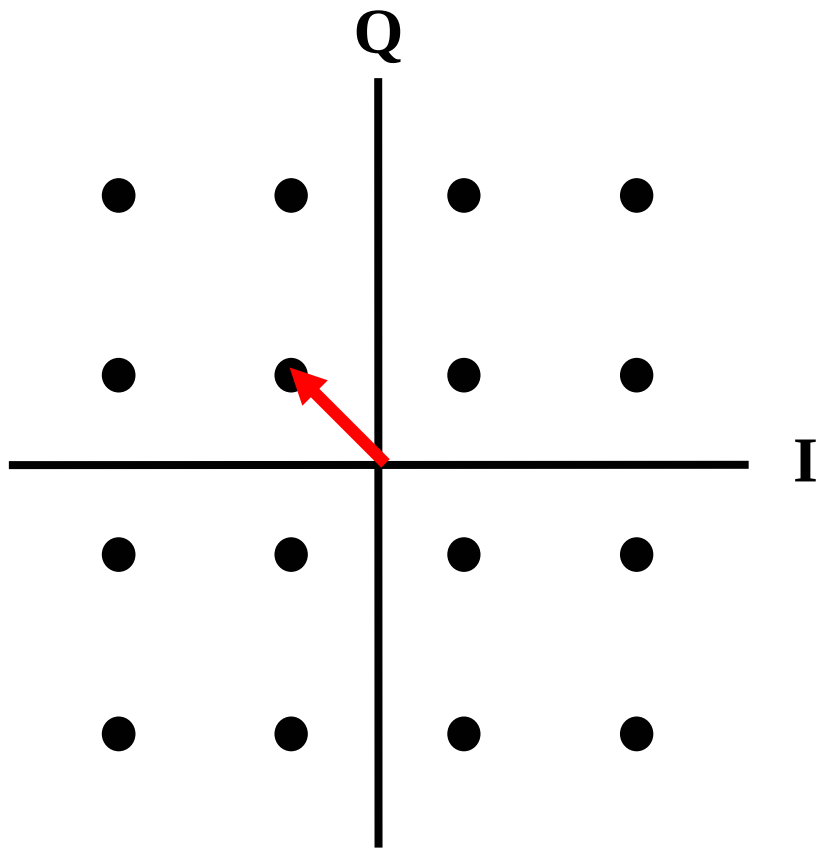
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	**135°**	**0.33**
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	**105°**	**0.75**
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
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1100	45°	0.33
1101	75°	0.75
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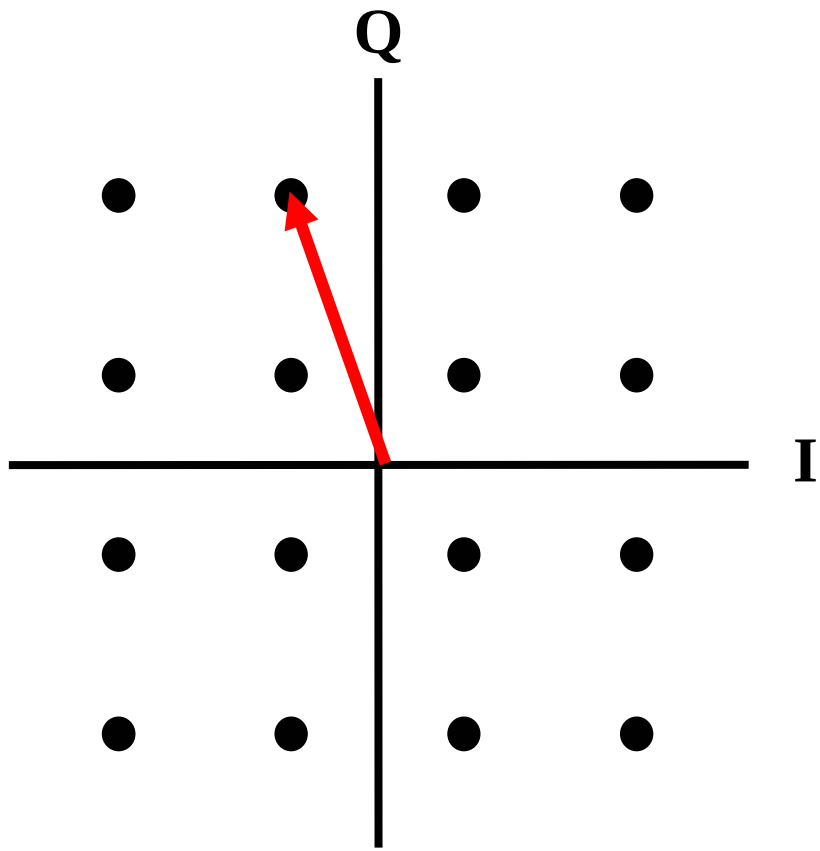
1111	45°	1.0



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0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
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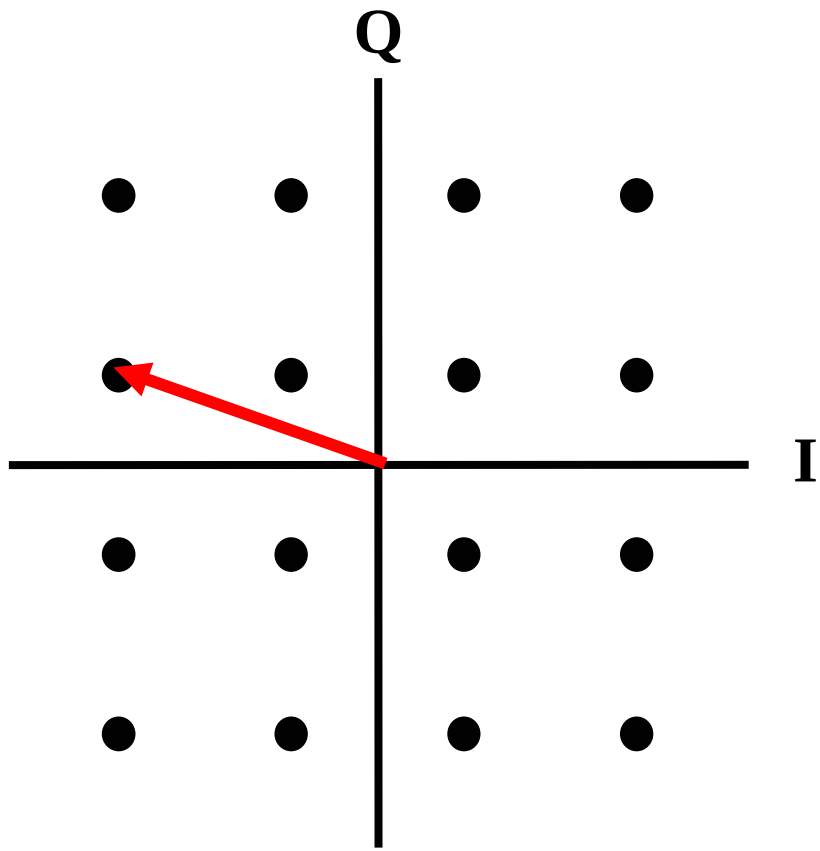
0100	135°	0.33
0101	105°	0.75
0110	**165°**	**0.75**
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



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0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
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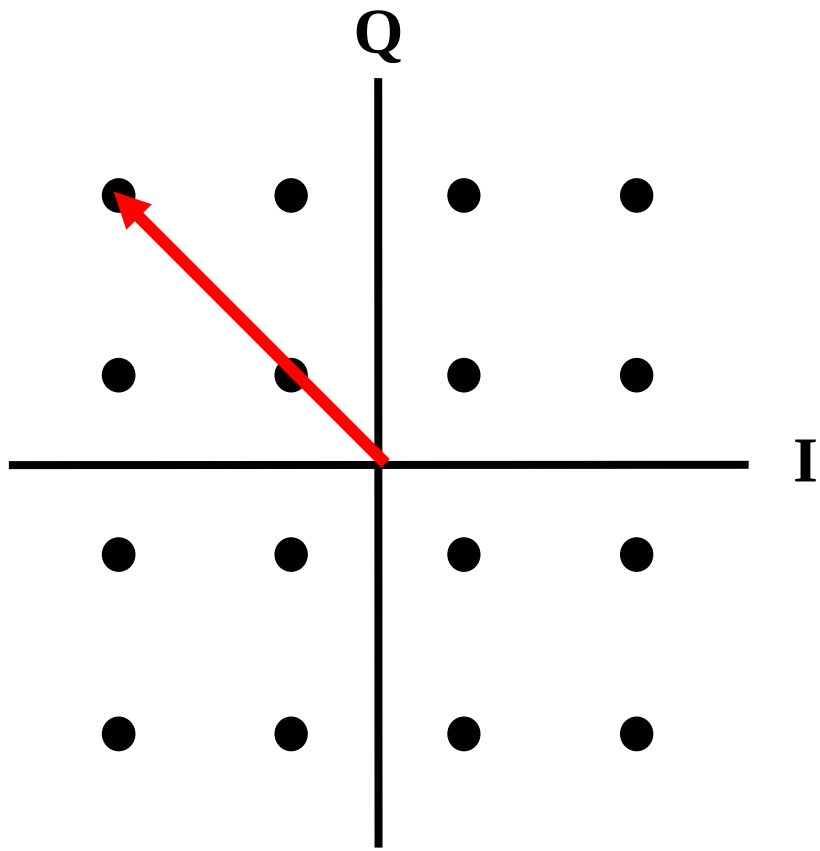
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	**135°**	**1.0**
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



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1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
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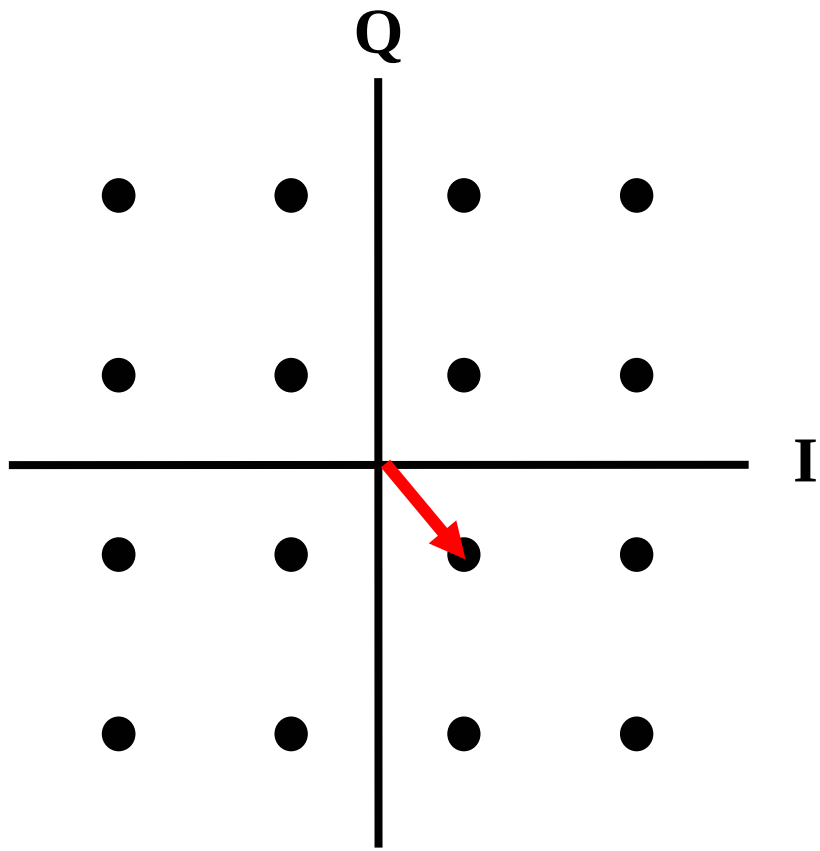

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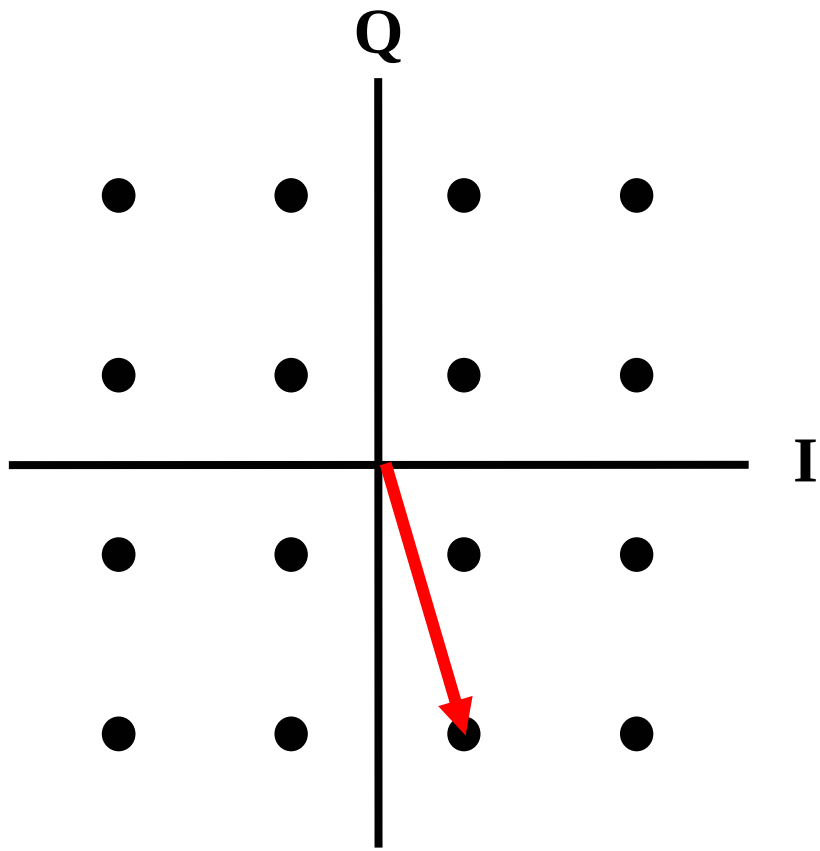
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	**285°**	**0.75**
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



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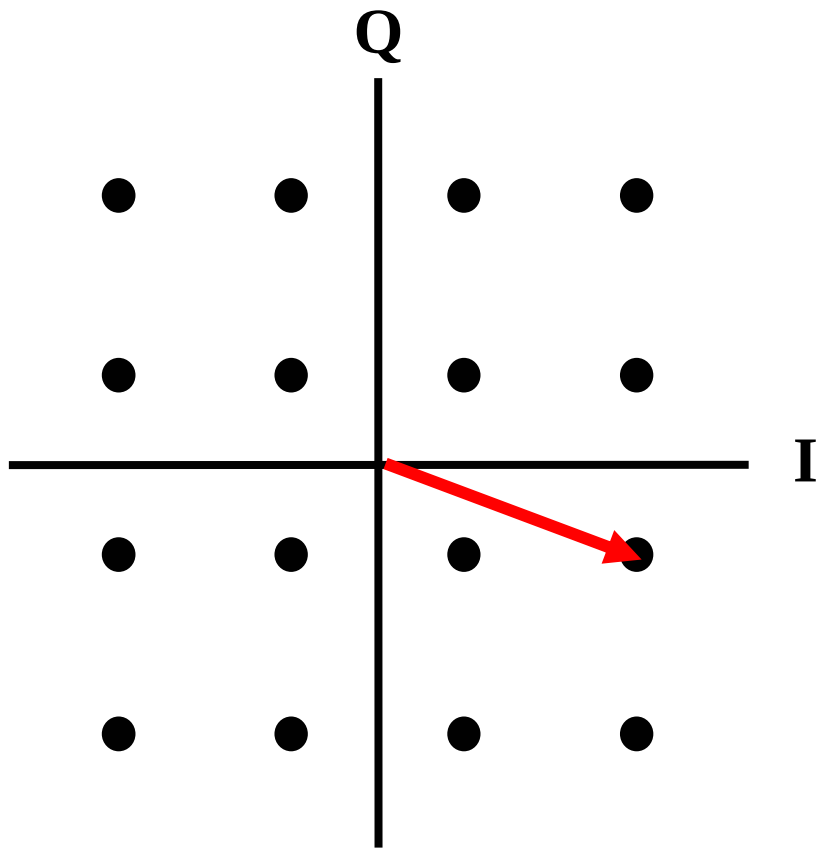

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0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
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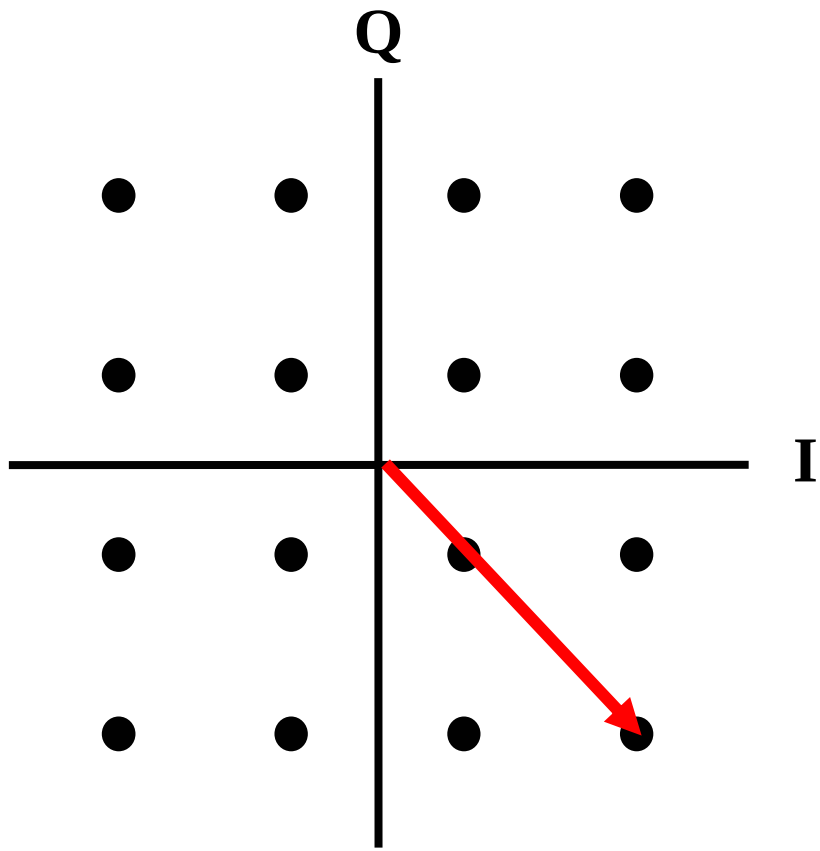
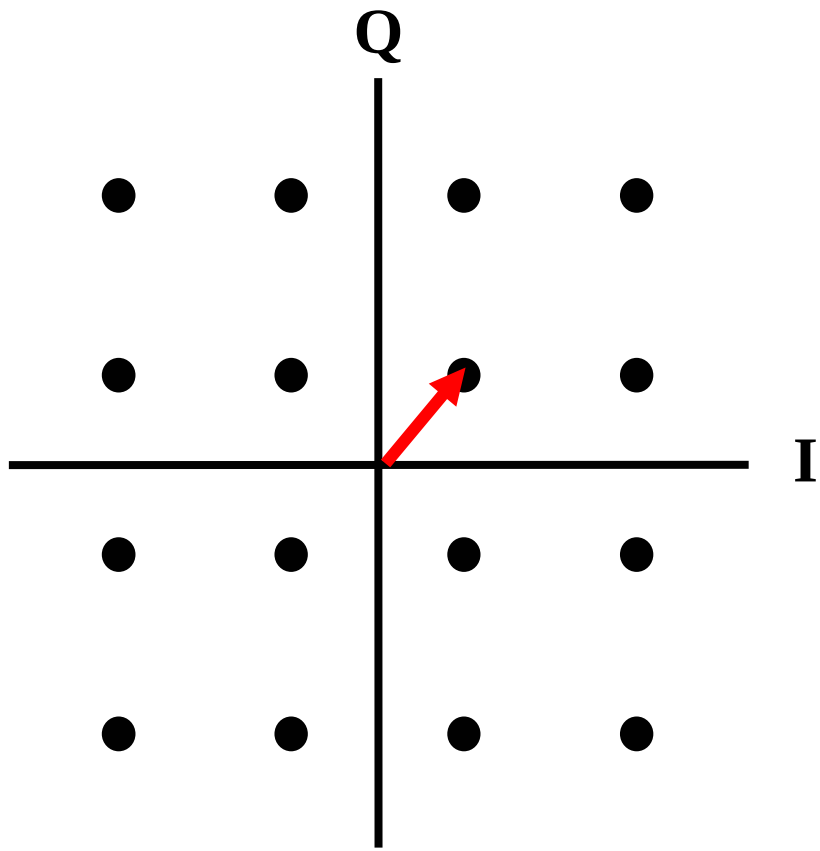
1111	45°	1.0



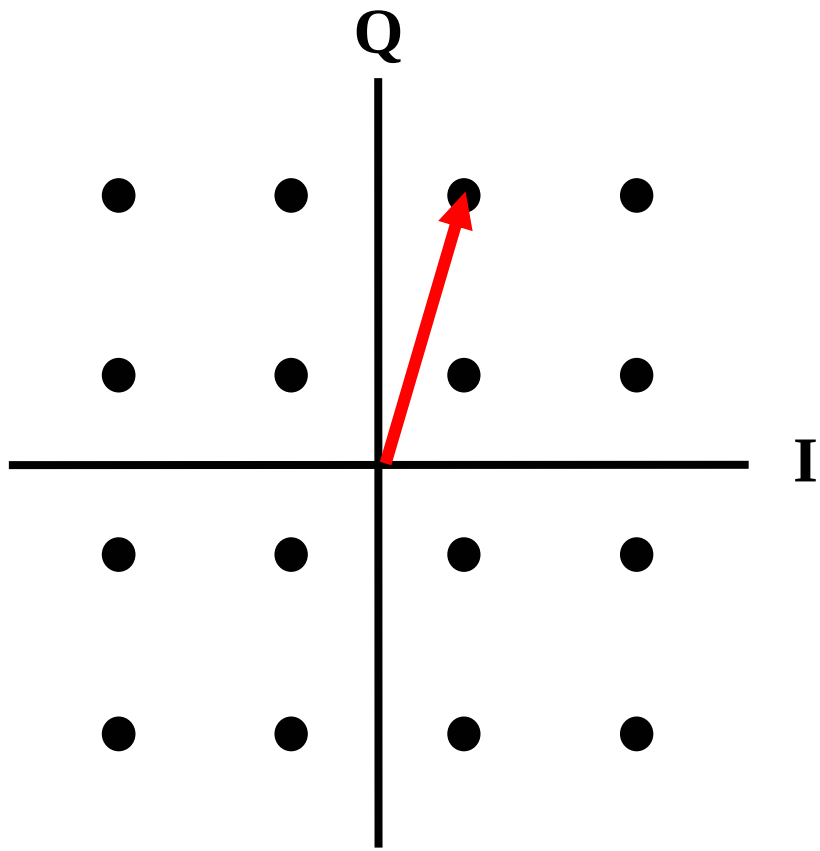
16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	45°	1.0



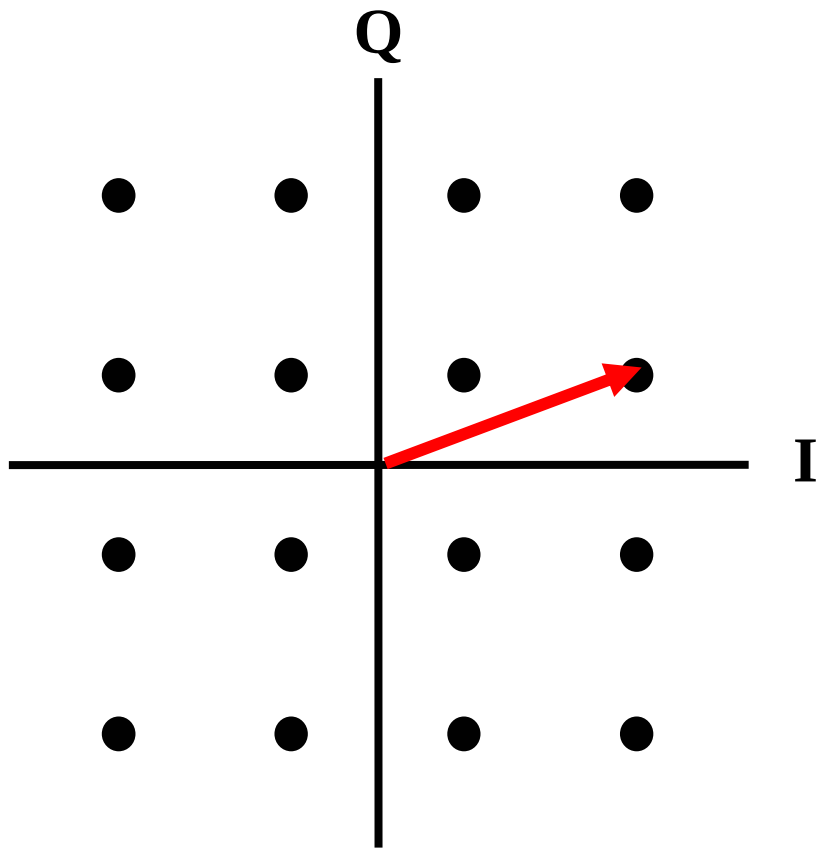
16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	**75°**	**0.75**
1110	15°	0.75
1111	45°	1.0



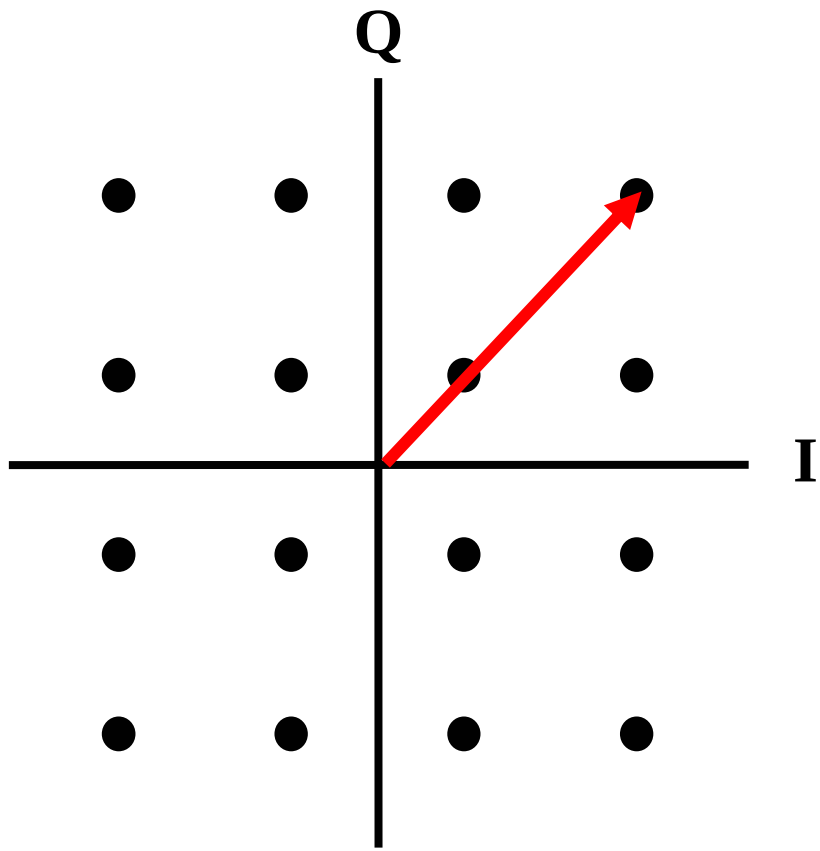
16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	**15°**	**0.75**
1111	45°	1.0

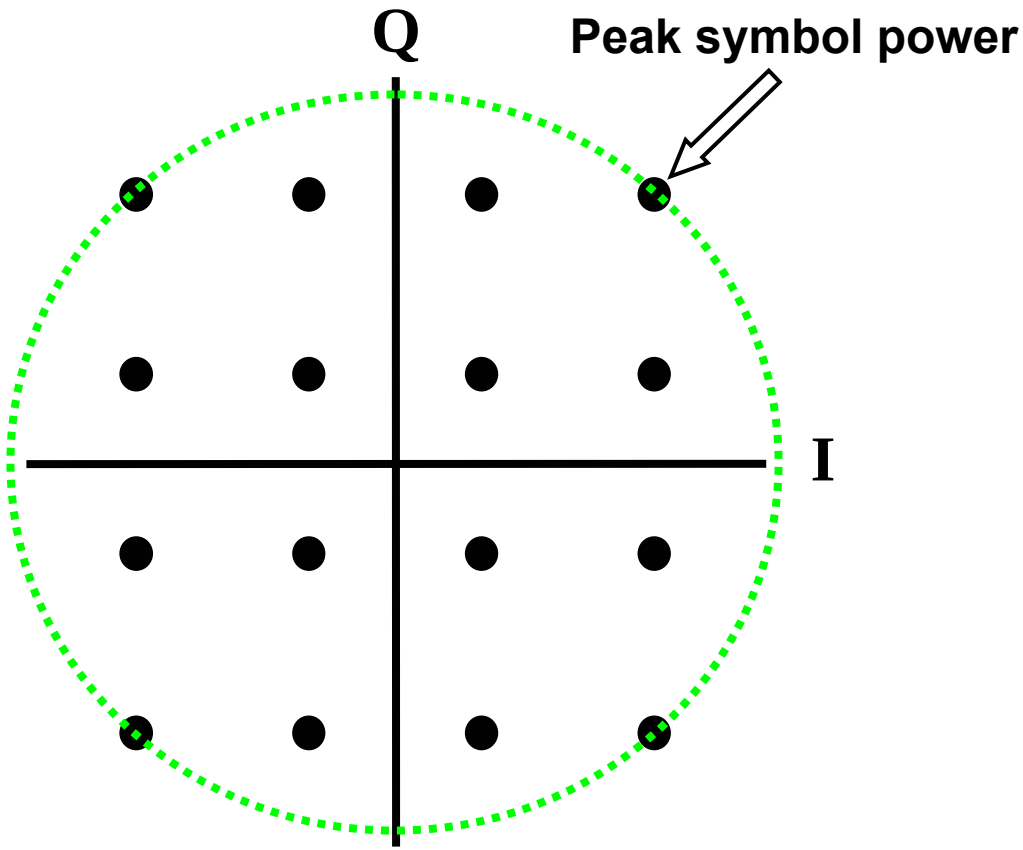


16-QAM Constellation

Symbol Transmitted	Carrier Phase	Carrier Amplitude
0000	225°	0.33
0001	255°	0.75
0010	195°	0.75
0011	225°	1.0
0100	135°	0.33
0101	105°	0.75
0110	165°	0.75
0111	135°	1.0
1000	315°	0.33
1001	285°	0.75
1010	345°	0.75
1011	315°	1.0
1100	45°	0.33
1101	75°	0.75
1110	15°	0.75
1111	**45°**	**1.0**

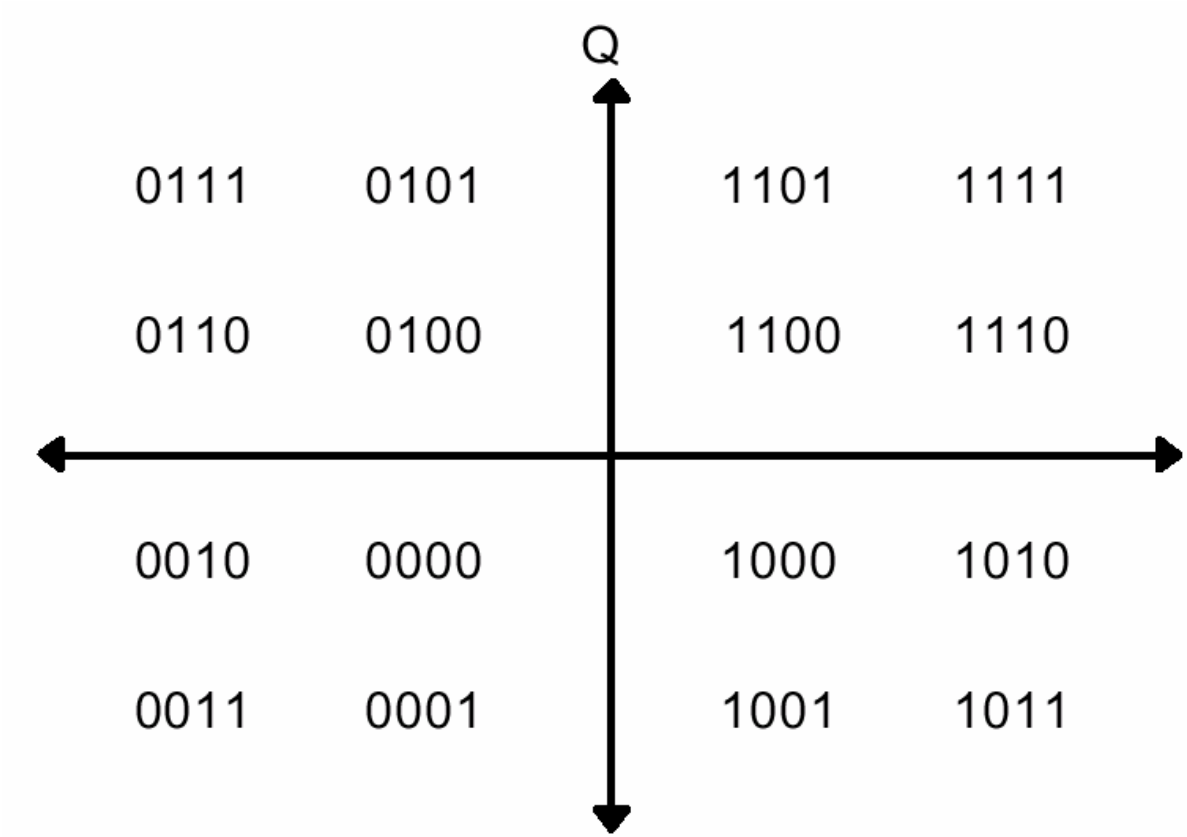


16-QAM Constellation



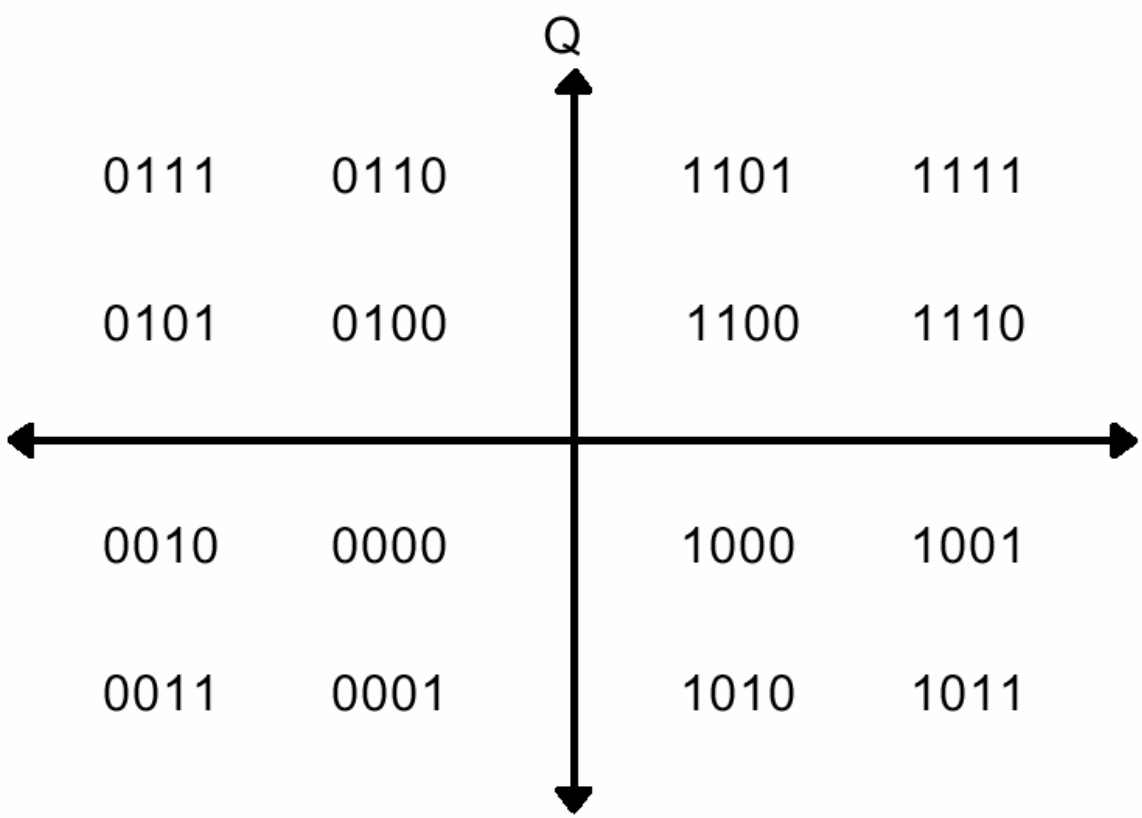
16-QAM Symbol Mapping

Gray-Coded Symbol Mapping



16-QAM Symbol Mapping

Differential-Coded Symbol Mapping



QPSK and 16-QAM in the Upstream

Channel bandwidth, MHz	Symbol rate, ksym/sec	QPSK raw data rate, Mbps	QPSK nominal data rate, Mbps	16-QAM raw data rate, Mbps	16-QAM nominal data rate, Mbps
0.200	160	0.32	~0.3	0.64	~0.6
0.400	320	0.64	~0.6	1.28	~1.2
0.800	640	1.28	~1.2	2.56	~2.4
1.60	1,280	2.56	~2.3	5.12	~4.8
3.20	2,560	5.12	~4.6	10.24	~9.0

Upstream C/N Ratio

- To achieve a $1x10^{-6}$ bit error rate (BER):

  QPSK requires 13.81 dB carrier-to-noise ratio (C/N or CNR)

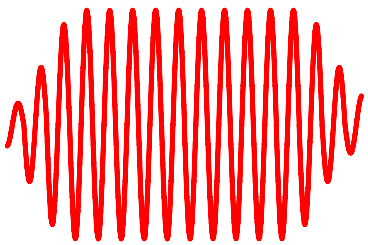
  16-QAM requires 20.92 dB C/N

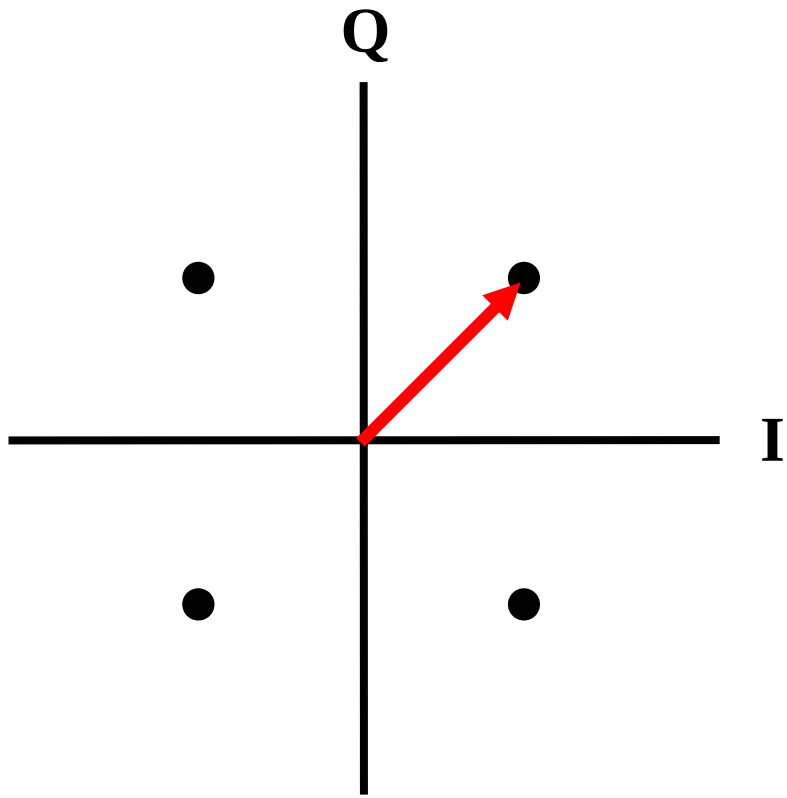
  These are theoretical values, and assume *additive white Gaussian noise* (AWGN) is the only impairment

- Forward error correction (FEC) buys another ~2 dB
- In order to maintain the same BER obtained with QPSK, the C/N must be ~7 dB better when 16-QAM is used
- DOCSIS assumes a minimum 25 dB carrier-to-noise, carrier-to-interference and carrier-to-ingress power ratios in the upstream, regardless of modulation format

What About Impairments?

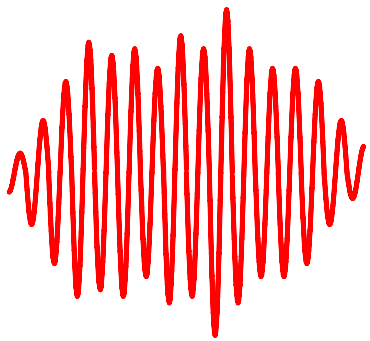
This is what is transmitted—the RF signal's instantaneous amplitude and phase represent the symbol "11"

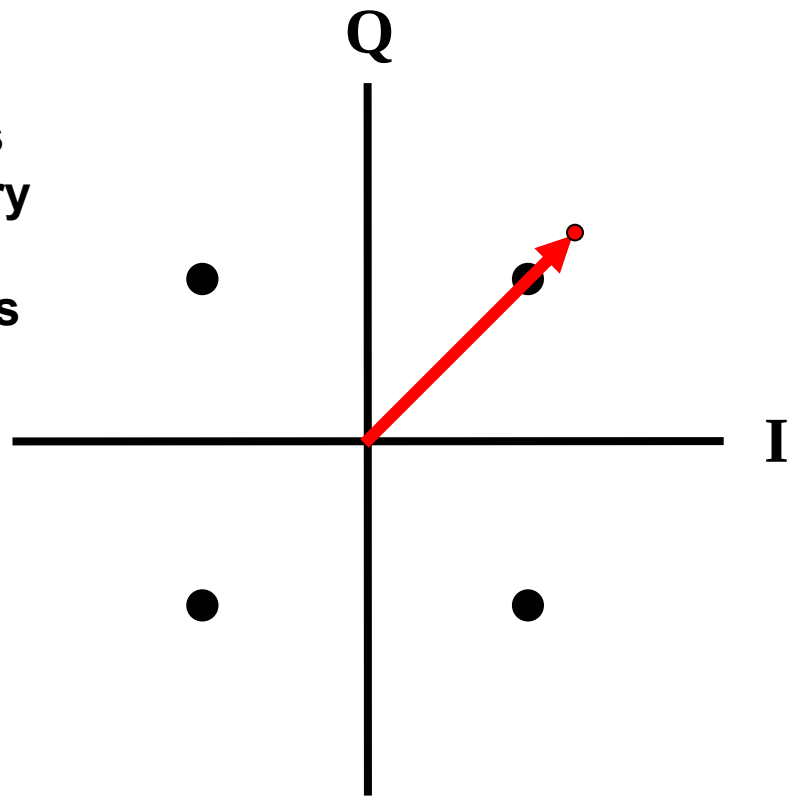




What About Impairments?

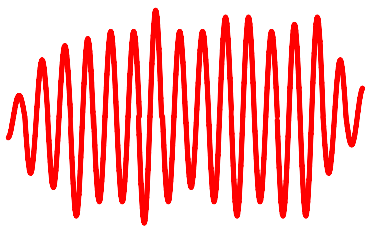
This is what is received after noise randomly mixes with the transmitted signal somewhere in the transmission path. Because the received RF signal's phase and amplitude didn't change very much from what was actually transmitted, the data receiver interprets the signal as "11".

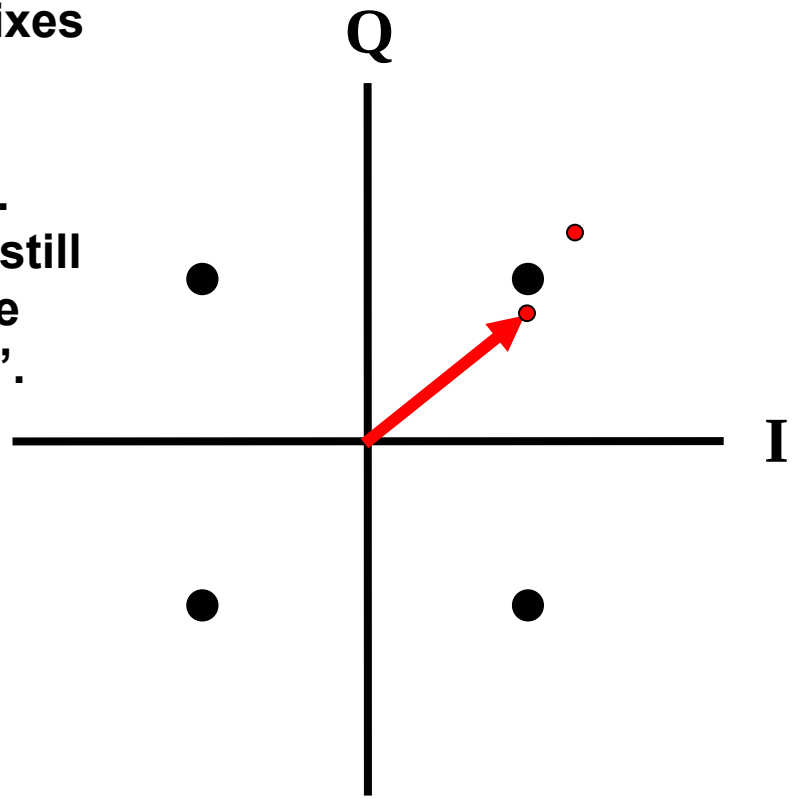




What About Impairments?

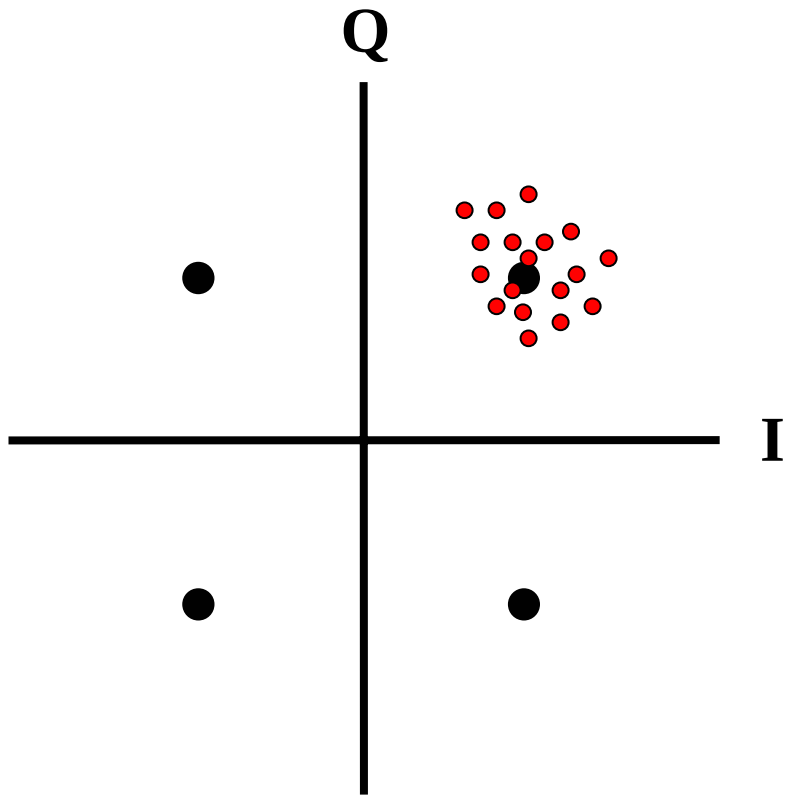
The next time the symbol “11” is transmitted, the RF signal randomly mixes with noise again. But this time the received signal’s amplitude is a little lower, and the phase is shifted slightly. The received phase and amplitude are still close enough to the ideal position to be interpreted by the data receiver as “11”.





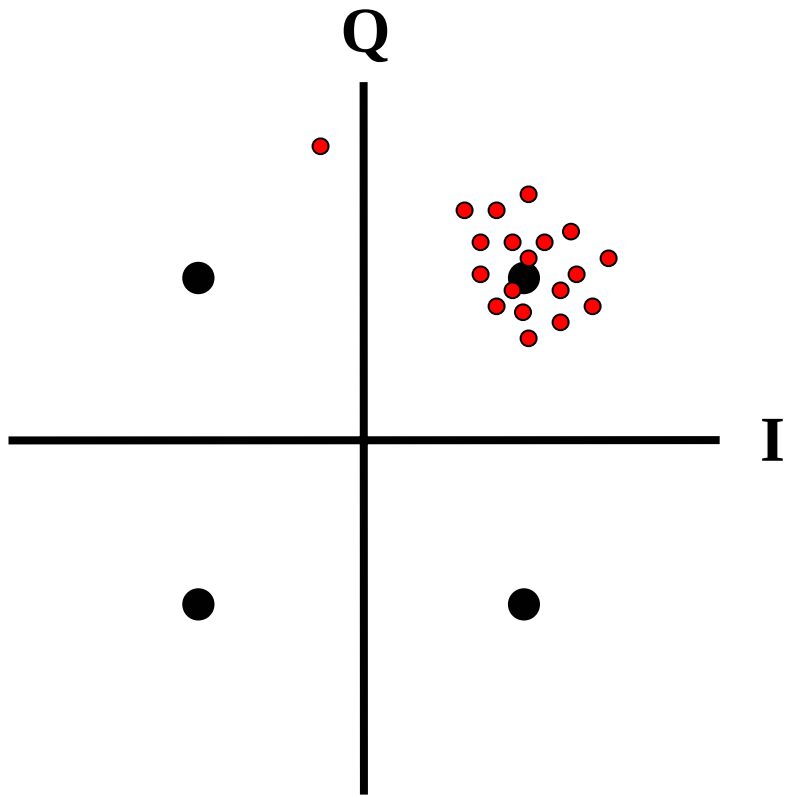
What About Impairments?

The same symbol transmitted multiple times mixes randomly each time with noise in the transmission path. As a result, each received symbol's plotted position on the constellation is slightly different. In this example, all of the received signals' phases and amplitudes are able to be interpreted as "11".



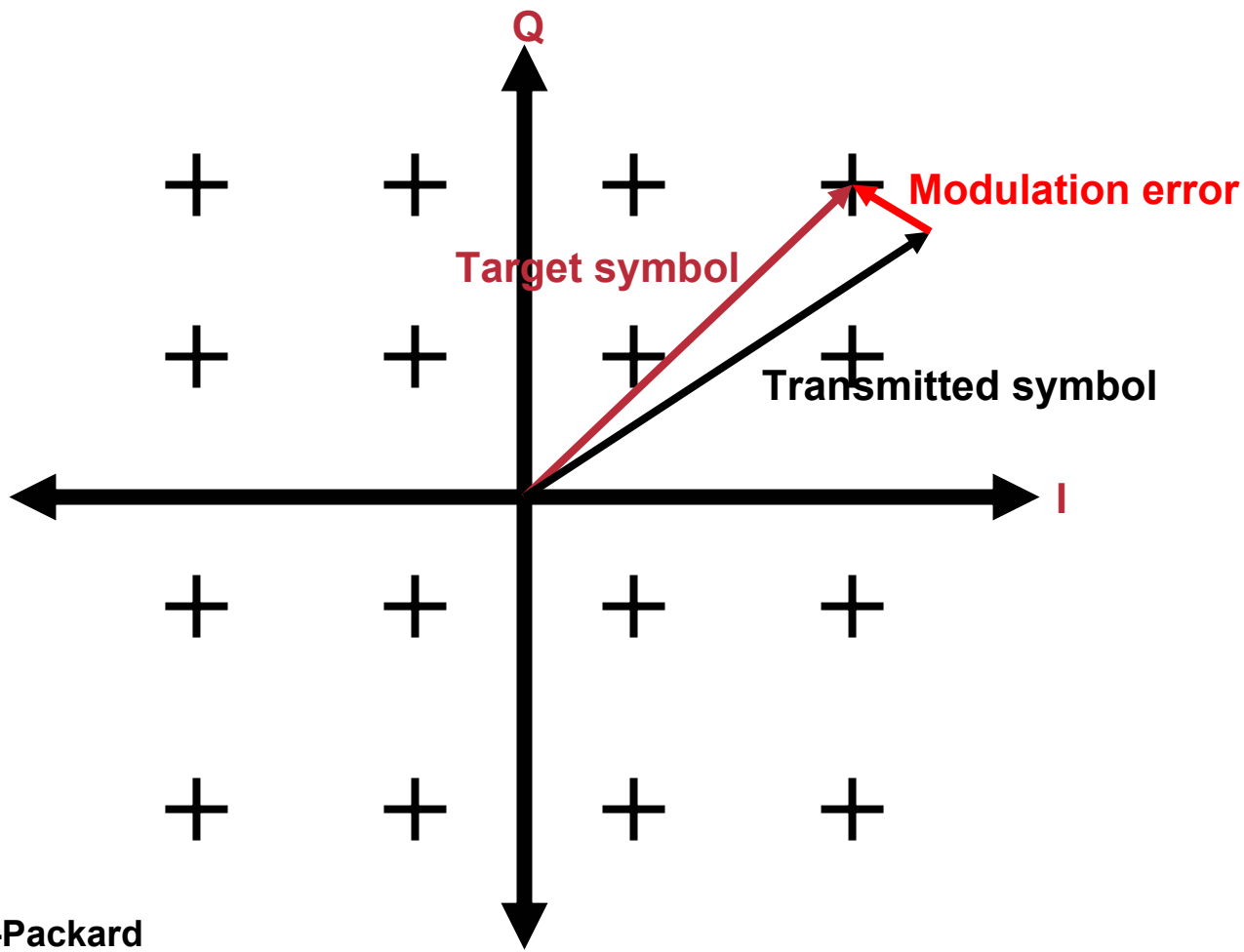
What About Impairments?

Here a large burst of noise mixes with the RF signal, causing the received phase and amplitude to be outside of the “decision boundary” for the desired symbol. The data receiver is not able to correctly interpret the received signal as “11”, so an error occurs.



Modulation Error Ratio: Modulation Quality

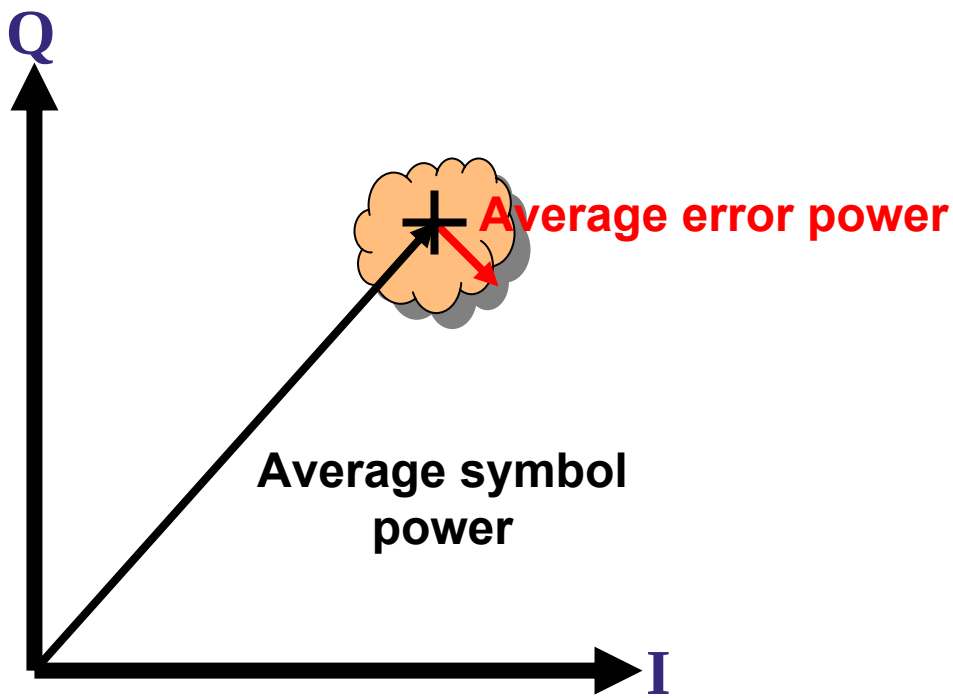
Modulation error = Transmitted symbol – **Target symbol**



Source: Hewlett-Packard

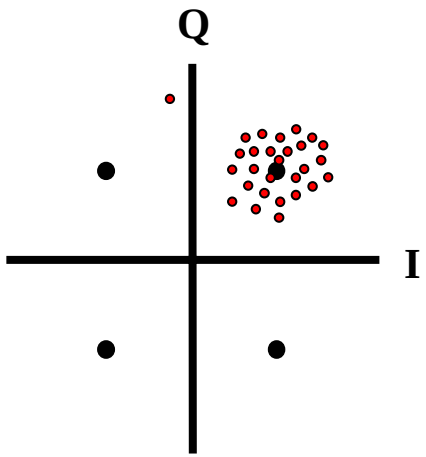
Modulation Error Ratio

MER = 10log(average symbol power/average error power)

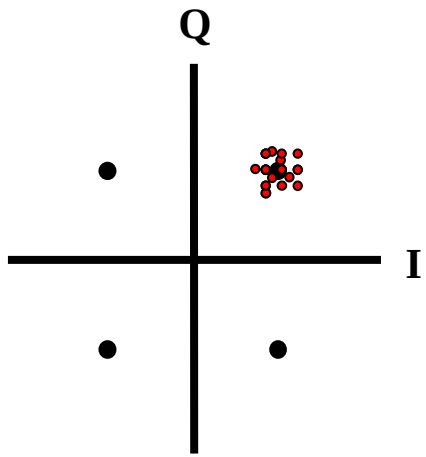


Source: Hewlett-Packard

Modulation Error Ratio



A large “cloud” of symbol points means low MER—this is not good!

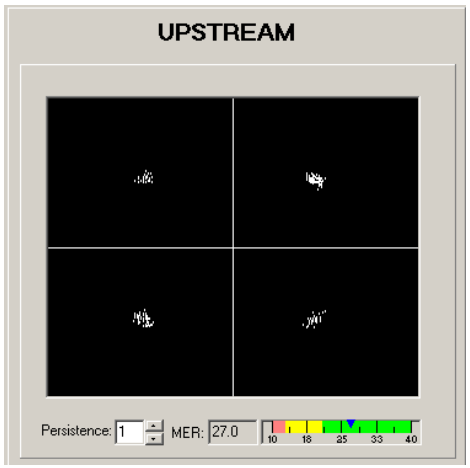


A small “cloud” of symbol points means high MER—this is good!

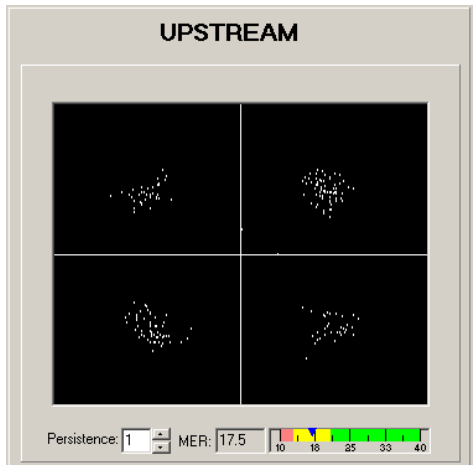
Modulation Error Ratio

- QPSK typically requires a minimum MER of 10~13 dB, depending on CMTS make/model
- Noise appears random
- CW produces “donut” shape

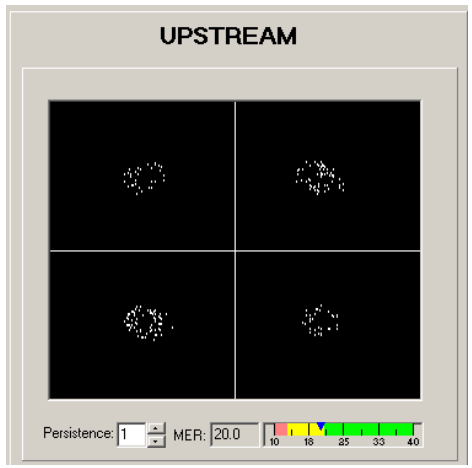
Ideal



Noise



CW Tone

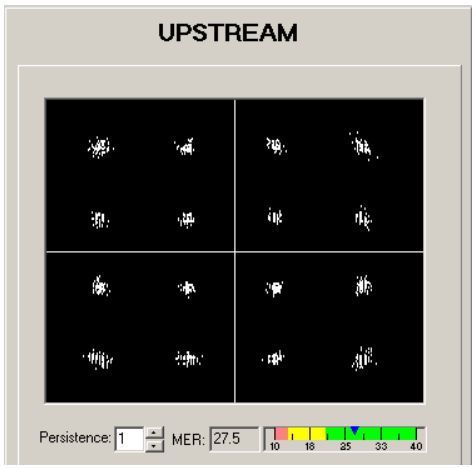


Courtesy of Filtronic Sigtek, Inc.

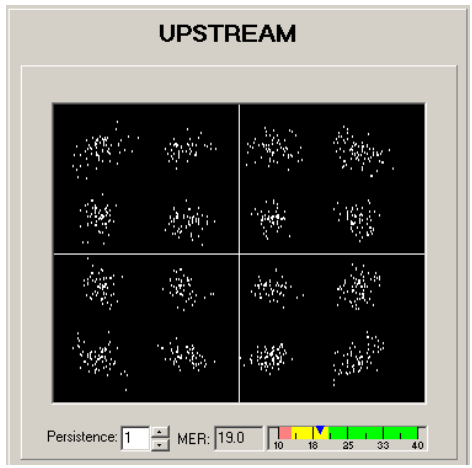
Modulation Error Ratio

- 16-QAM typically requires a minimum MER of 17~20 dB, depending on CMTS make/model
- Noise appears random
- CW produces “donut” shape

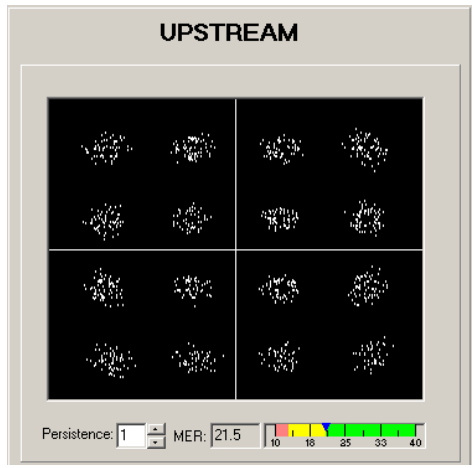
Ideal



Noise



CW Tone



Courtesy of Filtronic Sigtek, Inc.