# *Quadrature Modulation: Sines and Cosines*

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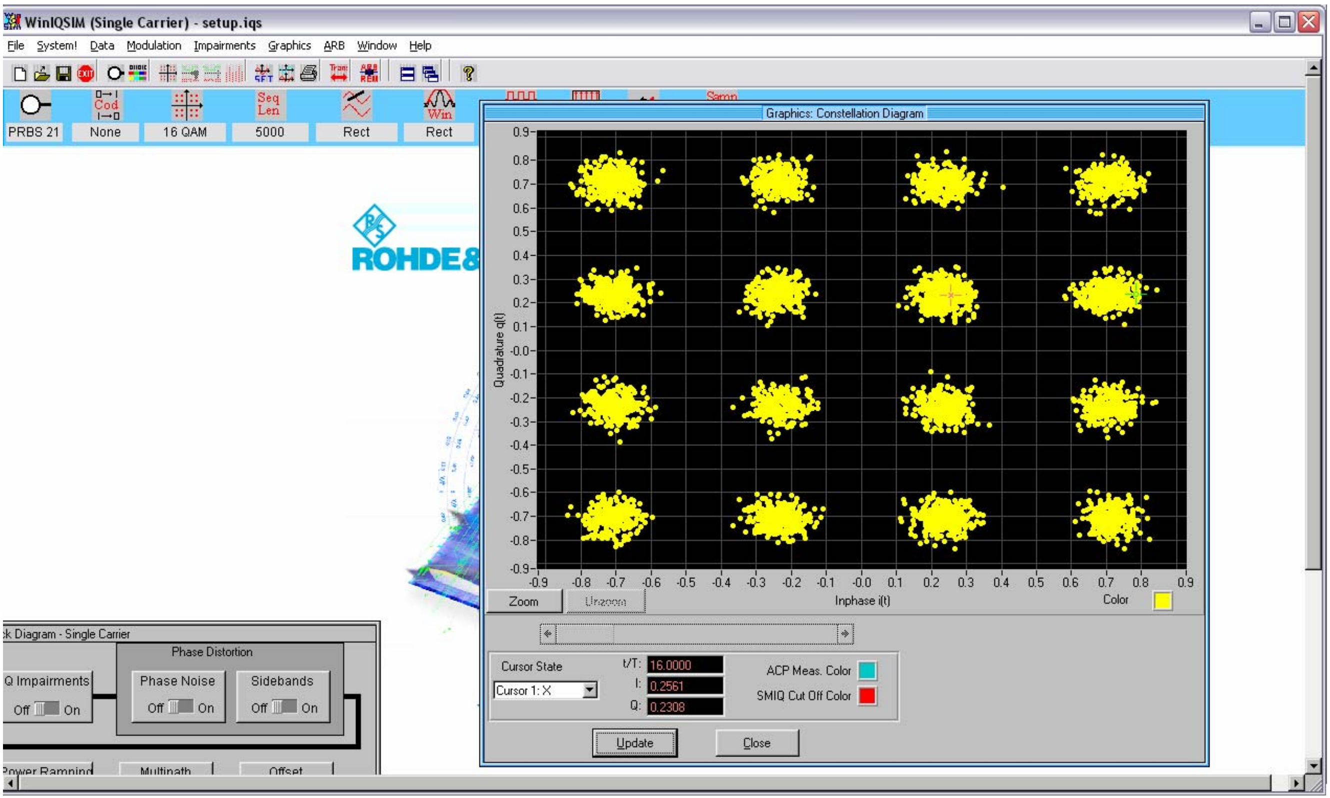
*Quadrature techniques are being used increasingly often to generate and process radio signals. A supplementary benefit is that older modulation methods such as FM and AM can also be demodulated easily using this technique. It also helps eliminate some annoying properties of receivers, in particular suppression of image frequencies. Furthermore, a quadrature AM (QAM) signal can be used to transmit twice as much information as an AM signal with the same bandwidth. This is especially nice considering how much information is transmitted on wireless channels these days.*

### *Quadrature demodulation*

***Figure 1*** *shows the basic block diagram of a quadrature demodulator. An RF signal is applied to the input of the demodulator. It consists of a sine-wave portion and a cosine-wave portion. In the upper mixer, the input signal is mixed with a cosine waveform generated in the receiver by the local oscillator (LO). The signal that appears at the output thus consists of two parts. The first part is a cosine waveform with a frequency equal to the difference between the frequency of the input signal and the frequency of the LO signal ($\omega_L/2\pi$), while the second part ($\omega_H/2\pi$) is again a cosine waveform with a frequency equal to the sum of the frequency of the input signal and the frequency of the LO signal. Only the first part remains after filtering.*

*This is doubtless nothing new for you. After mixing the two signals, you obtain a sum signal and a difference signal in terms of frequencies.*

*The bottom part of the demodulator is nearly the same, with the only significant difference being that here we use a sine-wave signal from the local oscillator. The output of this stage again has a cosine waveform with frequency of $\omega_H/2\pi$, plus a* ***sine*** *waveform with a frequency of $\omega_L/2\pi$. Only the sine waveform remains after filtering.*




### *AM demodulation*

*Now let's examine the above circuit diagram more closely using an AM signal. Let's assume that a radio station transmits at a frequency of 700 kHz. This gives a value for $\omega$ of $2\pi \times 700$ kHz ≈ 4400 rad/s. The formula is thus RF = a(t)cos(4400t), where a(t) is the signal we want to transmit. Here the LO is tuned to exactly this frequency (and has exactly the same phase), which means that $\omega_L$ is equal to 0. After filtering, you are left with the signal a(t)cos(0). As you probably remember from your schooldays (and if not, you can check it on your calculator), cos(0) = 1. In other words, signal I(t) is identical to the transmitted signal a(t).*

*The same story holds true for the lower part, with the major difference that Q(t) is equal to a(t)sin(0). As you also know that sin(0) = 0, the result here is Q(t) = 0. The Q signal thus does not contain any information at all.*

*If we now suppose that the AM transmitter has a 90-degree phase lag, the RF signal can be described by the expression a(t)cos((4400t) – 0.5π), which is the same as a(t)sin(4400t). In this case, I(t) will be equal to a(t)sin(0), which means that the I signal is always null. By contrast, the Q(t) signal will be equal to a(t)cos(0), which is simply a(t).*

*Note that a major advantage of quadrature modulation is that it is also possible to transmit negative signals. With normal AM, only the amplitude of the RF signal contains the information. With quadrature modulation, a negative signal at the transmitter end will also generate a negative signal in the I(t) and (Q(t) outputs. This doubles the dynamic range of the transmitter.*

### *Two for the price of one*

*Now we're going to makes things really interesting: two AM transmitters on the same frequency without any mutual interference! Is that possible? Yes, it's certainly possible if you use quadrature modulation and demodulation. Suppose your favourite rock-radio and jazz-club broadcasters have joined together as a result of a merger. The idea is that now the two signals rock(t) and jazz(t) will be transmitted simultaneously on the same frequency. The objective here is to increase operational efficiency, since only one transmitter is necessary.*

*This is possible if the rock(t) signal is modulated using a cosine wave while the jazz(t) signal is modulated using a sine wave. The resulting RF signal has the following formula:* $RF = rock(t)\cos(4400t) + jazz(t)\sin(4400t)$.

*Your faithful receiver is still tuned to exactly the same frequency. Using the previously described analysis, you can see that signal I(t) is equal to* $[rock(t) \times 1] + [jazz(t) \times 0]$*, while signal Q(t) is equal to* $[rock(t) \times 0] + [jazz(t) \times 1]$*. If you want to listen to rock, you simply amplify signal I(t) and feed it to your sound system. If you're in the mood for jazz instead, you simply flip the switch to select the Q(t) signal.*

*Unfortunately, the aforementioned (fictitious) radio station would have a short life, since standard radios do not have I/Q selector switches. Even if they did, you would have to adjust the LO very precisely to the right frequency and the right phase, since otherwise the scheme described above wouldn't work very well. If the LO frequency were offset by only 0.25 Hz, the phase difference between the signals would be 90 degrees after 1 second, with the result that you would suddenly find yourself listening to jazz instead of rock. Another second later (180 degrees), you could once again enjoy rock music. This means you would need some sort of mechanism to ensure that the LO stayed in phase with the transmitter.*

### *Unit circle*

*We have to draw on a bit of mathematics to explain the following steps. A cosine can be 'generated' by using a circle in the X–Y plane with its centre at the origin (the unit circle shown in* ***Figure 2****). Suppose you have a vector (radial line) with a length of 1 that extends horizontally from the origin at time* $t = 0$*. Now let this vector rotate counter-clockwise at a constant speed. The X coordinate of the tip of the vector represents a cosine wave, corresponding to the angle the vector makes relative to the X axis at each point in time. If the vector starts from a position pointing vertically downward instead of a horizontal position, the X coordinate of the tip of the vector represents a sine wave corresponding to the angle the vector makes relative to the negative Y axis. A sine-wave signal can be described as a vector that points vertically downward at* $t = 0$*, while a cosine signal can be described as a vector pointing to the right at* $t = 0$*.*

### *QPSK*

*You can used AM modulation to transmit digital information. For instance, you can define a signal with the formula* $RF = 1 \times \cos(4400t)$ *as representing a logic '1', while a signal with the formula* $RF = -1 \times \cos(4400t)$ *represents a logic '0'. You can then use the I(t) signal in the receiver to recover the digital information. If you also use the Q signal in the same manner to transmit a second bit at the same time, you can double the capacity with the same bandwidth. The second bit appears in the receiver on the Q(t) signal.*

*If you transmit an RF signal with* $1 \times \cos(4400t) + 1 \times \sin(4400t)$*, you can regard this as a vector with its tip located at coordinates (1, -1). A vector with its tip at (1, 1) at* $t = 0$ *thus corresponds to* $1 \times \cos(4400t) + (-1) \times \sin(4400t)$*. There are ultimately four conceivable initial phases, which explains why this is called 'quadrature phase shift keying' (QPSK). The signal modulated using a cosine waveform is called the 'in-phase signal', while the second signal is called the 'quadrature signal'.*

### *QAM*

*Even more information can be transmitted by using 16-QAM modulation. This involves modulating both signals (sine and cosine) at a total of four different levels. They are –1.5, –0.5, +0.5, and +1.5. This means that there are four possible levels that you can choose from for the X coordinate (cosine) of the vector at* $t = 4$*, plus another four for the Y coordinate (–sine). There are thus 16 different states in total. This makes it possible to transmit four bits at a time.*

*256-QAM is commonly used nowadays, such as in wireless networks. This involves modulating both signals with 16 different levels, which means that eight bits can be transmitted at a time.*

### *Noise*

*The vector that was used to modulate the RF signal is determined for each bit group in turn in the receiver. As noise always occurs in real-life situations, this is done within certain accuracy limitations. If the software can no longer determine which 'box' a particular point belongs to, the transmitted information cannot be recovered. This why wireless networks sometimes drop back from 256-QAM to 16-QAM, since the latter scheme has better noise immunity. The disadvantage is that only half the maximum data rate is available.*

*If all this has piqued your interest in experimenting with various types of digital modulation, you can download the 'WinIQsim' program free of charge from the Rhode & Schwarz website. This program can be used to simulate a variety of modulation methods and filters.*

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*Web link*

[http://www2.rohde-schwarz.com](http://www2.rohde-schwarz.com)