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What is I/Q Data?

Overview

This tutorial is part of the National Instruments Measurement Fundamentals series. Each tutorial in this series teaches you a specific topic of common measurement applications by explaining the theory and giving practical examples. This tutorial covers a brief overview and introduction to I/Q data as it relates to RF and wireless systems.

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Put in its simplest form, I/Q data shows the changes in magnitude (or amplitude) and phase of a sine wave. If amplitude and phase changes are made in an orderly, predetermined fashion, one can use these amplitude and phase changes to encode information upon a sine wave; a process known as modulation.

Modulation is the process of changing a higher frequency carrier signal in proportion to a lower frequency message, or information, signal. I/Q data is highly prevalent in RF communications systems, and more generally in signal modulation, because it is a convenient way to modulate signals. This discussion covers the theoretical background of I/Q data as well as practical considerations which make the use of I/Q data in communication so desirable.

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Background on Signals

Signal modulation involves changes made to sine waves in order to encode information. The mathematical equation representing a sine wave is as follows:

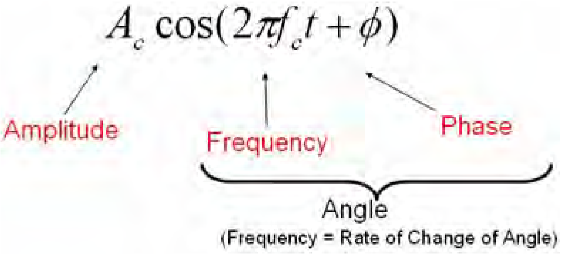


Figure 1: Equation of a Sine Wave

If we think about possible sine wave parameters that we can manipulate, the equation above makes it clear we are limited to making changes to the amplitude, frequency, and phase of a sine wave to encode information. Frequency is simply the rate of change of phase of a sine wave (frequency is the first derivative of phase), so these two components of the sine wave equation can be collectively referred to as the phase angle. Therefore, we can represent the instantaneous state of a sine wave with a vector in the complex plane containing amplitude (magnitude) and phase coordinates in a polar coordinate system.

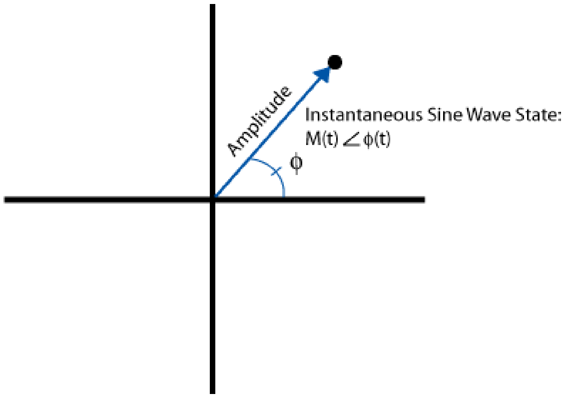


Figure 2. Polar Representation of a Sine Wave

In the graphic above, the distance from the origin to the black point represents the amplitude (magnitude) of the sine wave, and the angle from the horizontal axis represents the phase. Thus, the distance from the origin to the point will remain fixed as long as the amplitude of the sine wave is not changing (modulating). The phase of the point will change according to the current state of the sine wave. For example, a sine wave with a frequency of 1 Hz (2π radians/second) rotates counter-clockwise around the origin at a rate of one revolution per second. If the amplitude doesn't change during one revolution, the dot maps out a circle around the origin with radius equal to the amplitude along which the point will travel at a rate of one cycle per second.

Because phase is a relative measurement, imagine that the phase reference used is a sine wave of frequency equal to the sine wave that is being represented by the amplitude and phase points. If the reference sine wave frequency and the plotted sine wave frequency are the same, then the rate of change that the phase of the two signals experience will be the same, and the rotation of the sine wave around the origin will become stationary. In this case, a single amplitude/phase point can be used to represent a sine wave of frequency equal to the reference frequency. Any phase rotation around the origin indicates a frequency difference between the reference sine wave and the sine wave being plotted. We will return to this point later.

Up to this point, this tutorial has covered amplitude and phase data in a polar coordinate system. All the concepts discussed above apply to I/Q data, and in fact, I/Q data is merely a translation of amplitude and phase data from a polar coordinate system to a cartesian (X,Y) coordinate system. Using trigonometry, you can now convert the polar coordinate sine wave information into cartesian I/Q sine wave data. These two representations are equivalent and contain the exact same information, just in different forms. This equivalence is show in Figure 3.

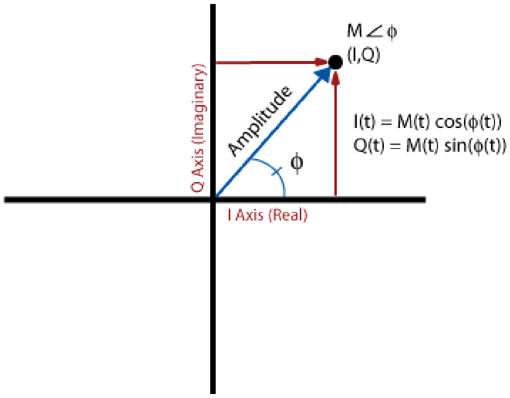
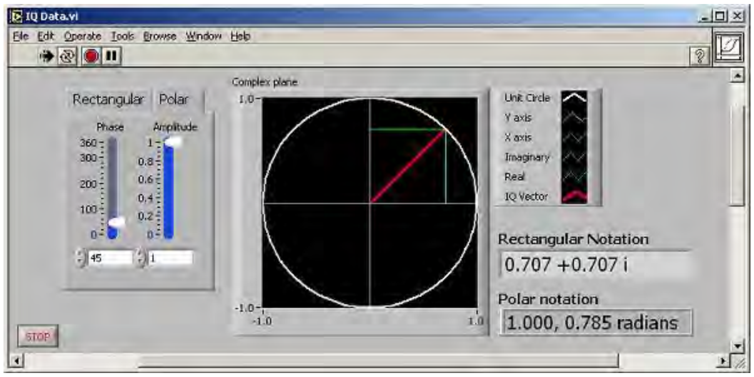


Figure 3. I and Q Represented in Polar Form

The figure below shows a LabVIEW example demonstrating the relationship between polar and cartesian coordinates.



Phase: 45

Amplitude: 1

Rectangular Notation: 0.707 +0.707 i

Polar notation: 1.000, 0.785 radians

[+] Enlarge Image

Figure 4: I/Q Data in LabVIEW

I/Q Data in Communication Systems

At this point, we have discussed technically what I/Q data is, but to explain why I/Q data is used, we must first discuss modulation basics.

RF communication systems use advanced forms of modulation to increase the amount of data that can be transmitted in a given amount of frequency spectrum. Signal modulation can be divided into two broad categories: analog modulation and digital modulation. *Analog* or *digital* refers to how the data is modulated onto a sine wave. If analog audio data is modulated onto a carrier sine wave, then this is referred to as analog modulation. If analog audio data is sampled by an analog to digital converter (ADC) with the resulting digital bits modulated onto a carrier sine wave, this is digital modulation because digital data is being encoded. Both analog modulation and digital modulation are performed by changing the carrier wave amplitude, frequency, or phase (or combination of amplitude and phase simultaneously) according to the message data.

Amplitude modulation (AM), frequency modulation (FM), or phase modulation (PM) are all examples of analog modulation. With amplitude modulation, the carrier sine wave amplitude is modulated according to the message signal. The same idea holds true for frequency and phase modulation.

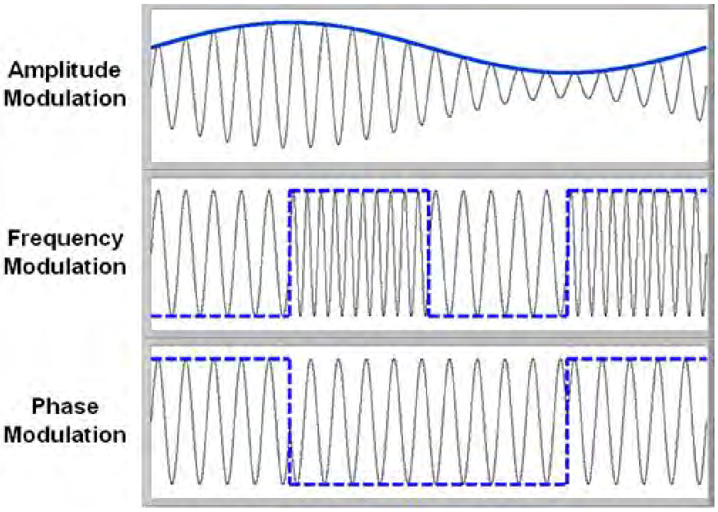


Figure 5. Time Domain of AM, FM, and PM Signals

Figure 5 represents various analog techniques—AM, FM, and PM—applied to a carrier signal. In the AM case, the message signal is the blue sine wave that forms the "envelope" of the higher frequency carrier sine wave. In the FM case, the message data is the dashed square wave. As the figure illustrates, the resulting carrier signal changes between two distinct frequency states. Each of these frequency states represents the high and low state of the message signal. If the message signal were a sine wave in this case, there would be a more gradual change in frequency, which would be more difficult to see. In the PM case, notice the distinct phase change at the edges of the dashed square wave message signal.

Applying this to the earlier discussion, if only the carrier sine wave amplitude changes with respect to time (proportional to the message signal), as is the case with AM modulation, we should see changes in the I/Q plane only with respect to the distance from the origin to the I/Q points. This is evidenced by the following image:

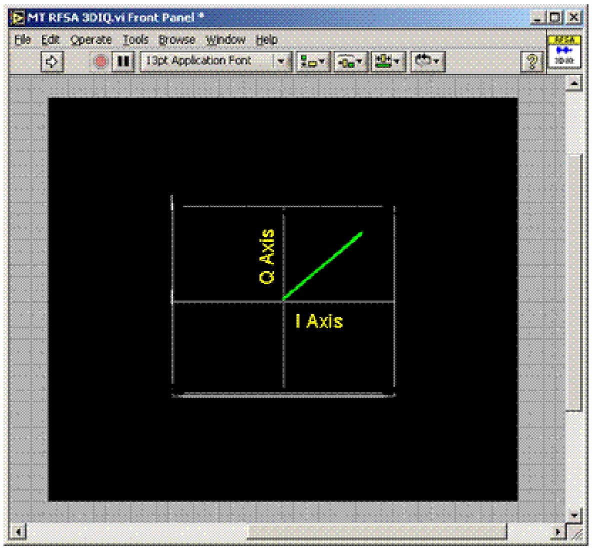


Figure 6. I/Q Data in the Complex Domain

The preceding figure shows the I/Q data points vary in amplitude only, with the phase fixed of 45 degrees. We cannot tell from Figure 6 the nature of the message signal—only that it is amplitude modulated. However, if we can see how the I/Q data points vary in magnitude with respect to time, we can essentially see a representation of the message signal. Using LabVIEW's 3D graph control, we can show the third axis of time to illustrate the message signal.

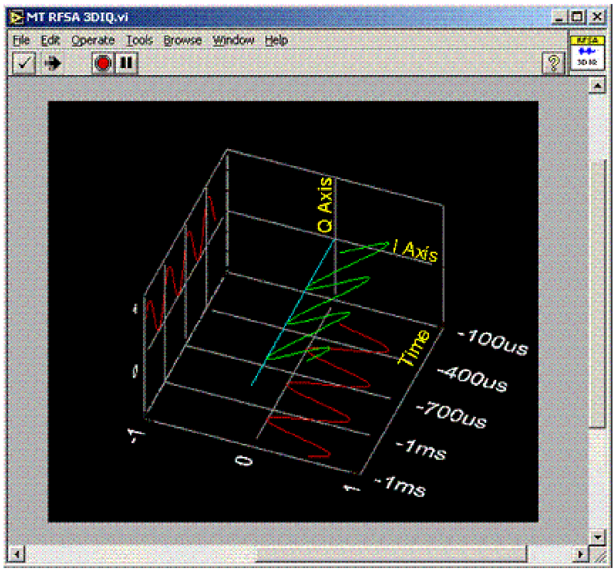


Figure 7. Representation of Magnitude vs. Time

Figure 7 shows the same data as the 2D I vs. Q plot in Figure 6. The magnitude of the signal trace modulates in a sinusoidal pattern indicating that the message signal is a sine wave. The green trace represents the amplitude and phase data in a polar coordinate system, while the red traces represent the projections of this waveform onto the I and Q axes, representing the individual I and Q waveforms.

We can show the same type of example using PM. An image of the same message signal sine wave using PM instead of AM is shown below.

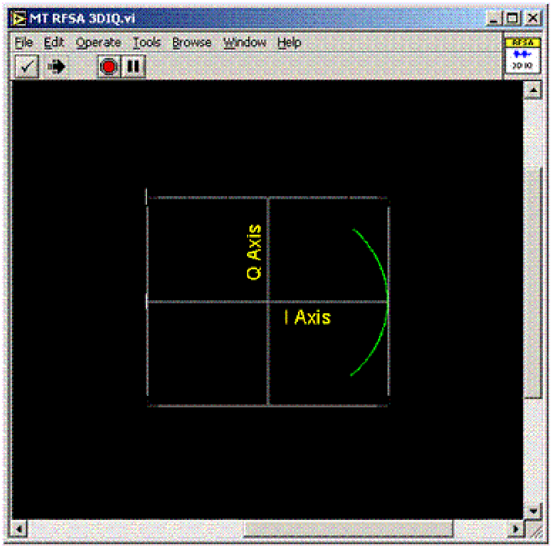


Figure 8. Polar Representation of Phase vs. Time

Once again, we can tell that the message signal is phase modulated as the amplitude is constant but the phase is changing (modulating). We cannot tell what the shape of the message signal is with respect to time, but we can tell the minimum and maximum signal levels of the message signal are represented by phase deviations of -45 degrees and +45 degrees respectively.

Once again, the time axis can be used to better understand this concept.

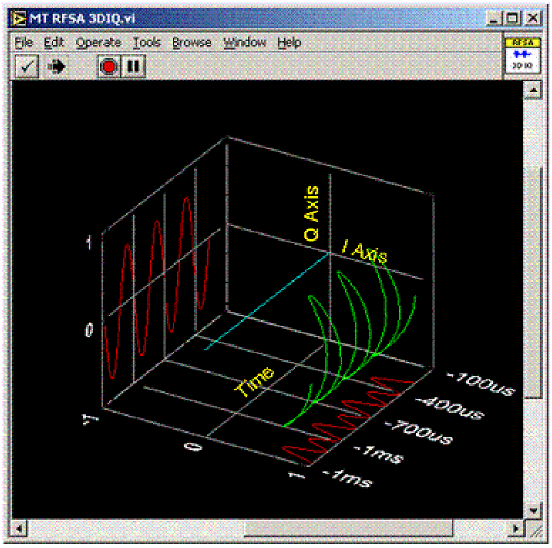


Figure 9. 3D Representation of Phase Modulation

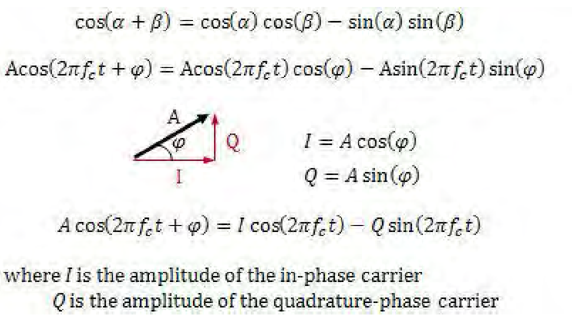
Figure 9, shown in the LabVIEW 3D graph, shows the green trace varying in a sinusoidal fashion with respect to time. The projections onto the I and Q axes represent the individual I and Q waveforms corresponding to the PM sine wave with fixed magnitude and oscillating phase.

In essence, the I/Q data represents the message signal. Because the I/Q data waveforms are cartesian translations of the polar amplitude and phase waveforms, it is not easy to visually tell what the nature of the message signal is from the I/Q data. To illustrate this, compare the red I and Q traces on the 3D I vs. Q plots in Figure 9 to the green trace in Figure 9. If we plot amplitude vs. time for the AM sine wave, we would display the message signal. If we plot the phase data vs. time for the AM sine wave, we would have a straight line. We would see sine waves for the I vs. time and Q vs. time waveforms as well, but the scale would be off, and this would not necessarily be the case for more complex digital modulation schemes where both amplitude and phase are modulated simultaneously.

So Why Use I/Q Data?

Because amplitude and phase data seem more intuitive, it would seem that we should use polar amplitude and phase data instead of cartesian I and Q data. However, practical hardware design concerns make I and Q data the better choice in this matter.

It is difficult to vary precisely the phase of a high-frequency carrier sine wave in a hardware circuit according to an input message signal. A hardware signal modulator that manipulates the amplitude and phase of a carrier sine wave would therefore be expensive and difficult to design and build, and, as it turns out, not as flexible as a circuit that uses I and Q waveforms. To understand how we to avoid manipulating the phase of an RF carrier directly, we first return to trigonometry.



$$\cos(\alpha+\beta)=\cos(\alpha)\cos(\beta)-\sin(\alpha)\sin(\beta)$$

$$A\cos(2\pi f_c t+\varphi)=A\cos(2\pi f_c t)\cos(\varphi)-A\sin(2\pi f_c t)\sin(\varphi)$$

$$I = A\cos(\varphi)$$

$$Q = A\sin(\varphi)$$

$$A\cos(2\pi f_c t+\varphi)=I\cos(2\pi f_c t)-Q\sin(2\pi f_c t)$$

where I is the amplitude of the in-phase carrier
Q is the amplitude of the quadrature-phase carrier

Figure 10. Mathematical Background of I/Q Modulation

According to the trigonometric identity shown in the first line of Figure 10, multiply both sides of the equation by *A* and substitute $2\pi f_c t$ in place of α and φ in place of β to arrive at the equation shown in line 2. Then substitute *I* for *A* cos(φ) and *Q* for *A* sin(φ) to represent a sine wave with the equation shown on line 3. Remember that the difference between a sine wave and a cosine wave of the same frequency is a 90-degree phase offset between them. The implications of this are very important. What this essentially means is that we can control the amplitude, frequency, and phase of a modulating RF carrier sine wave by simply manipulating the amplitudes of separate I and Q input signals! With this method, we no longer have to directly vary the phase of an RF carrier sine wave. We can achieve the same effect by manipulating the amplitudes of input I and Q signals. Of course, the second half of the equation is a sine wave and the first half is a cosine wave, so we must include a device in the hardware circuit to induce a 90-degree phase shift between the carrier signals used for the I and Q mixers, but this is a much simpler design issue than the aforementioned direct phase manipulation.

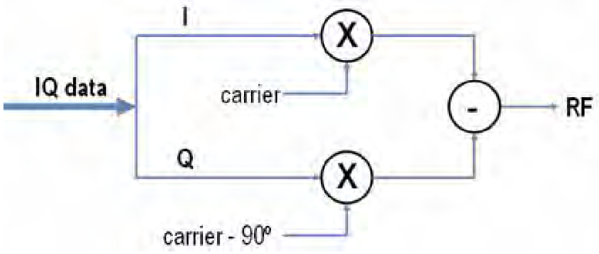


Figure 11. Hardware Diagram of an I/Q Modulator

Figure 11 shows a block diagram of an I/Q modulator. The circles with an 'X' represent mixers—devices that perform frequency multiplication and either upconvert or downconvert signals (upconverting here). The I/Q modulator mixes the I waveform with the RF carrier sine wave, and mixes the Q signal with the same RF carrier sine wave yet with a 90-degree phase offset. The Q signal is subtracted from the I signal (just as in the equation shown in line 3 in Figure 10) producing the final RF modulated waveform. In fact, the 90-degree shift of the carrier is the source of the names for the I and Q data—I refers to in-phase data (because the carrier is in phase) and Q refers to quadrature data (because the carrier is offset by 90 degrees). This technique is known as quadrature upconversion and the same I/Q modulator can be used for any modulation scheme. This is because the I/Q modulator is merely reacting to changes in I and Q waveform amplitudes, and I and Q data can be used to represent any changes in magnitude and phase of a message signal. The flexibility and simplicity (relative to other options) of the design of an I/Q modulator is the reason for its widespread use and popularity.

Related NI Hardware

Customers interested in this topic were also interested in the following NI products:

- NI RF & Communications Platform
- NI 5663 6.6 GHz RF Vector Signal Analyzer
- NI 5673 6.6 GHz RF Vector Signal Generator
- NI 5660 2.7 GHz RF Vector Signal Analyzer
- NI 5671 2.7 GHz RF Vector Signal Generator
- NI RF Switch Hardware
- NI Spectral Measurements Toolkit Software
- NI Modulation Toolkit Software

Conclusions

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