CONTENTS

5.0 Phase Modulation

Objectives

This section will:

- Review the basic PSK modulation schemes
- Examine the various QAM modulators
- Examine the various ways to recover the carrier

Phase modulation is most commonly used to convey digital signals. One of the very best articles on digital modulation can be found at:

Digital Modulation by Hewlett Packard

5.1 Phase Modulation

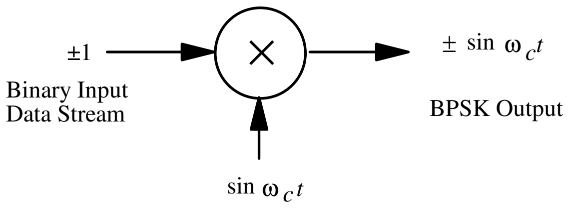
All high performance modems today use some form of phase modulation.

5.1.1 BPSK Modulator

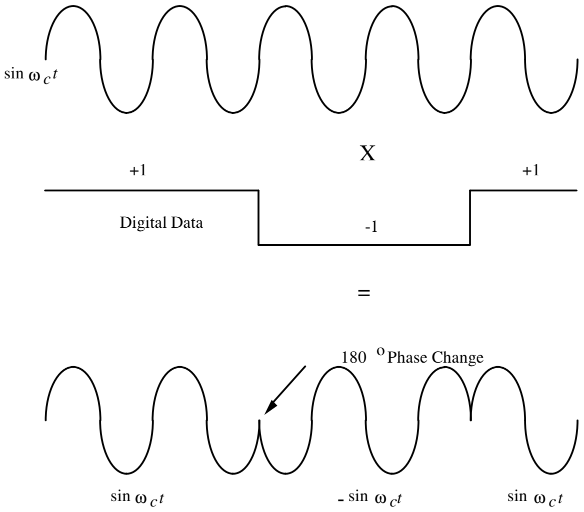
A BFSK System - Part 1 by Elanix

A BFSK System - Part 2 by Elanix

This is the simplest type of PSK modulator since it has only two output phase states. It uses a multiplier, which can be an IC or ring type.

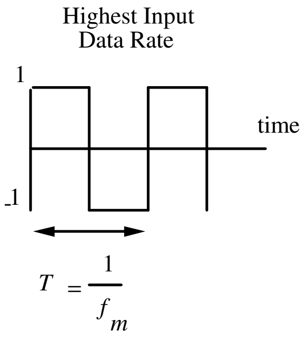


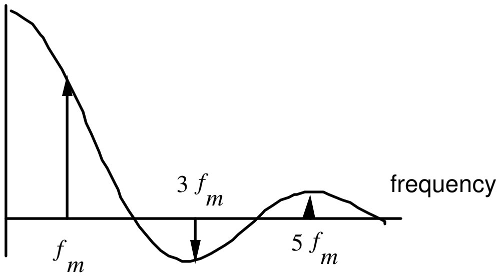
The output has two phase states:



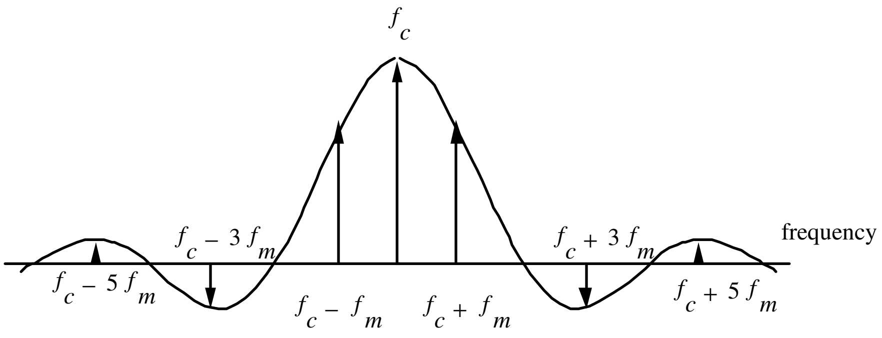
In the above illustration, the duration of each of the phase states corresponds to one signaling element or baud. The baud rate is therefor equal to the bit rate.

The spectrum of the BPSK signal will depend upon the data being transmitted, but it is very easy to sketch it for the highest data rate input.



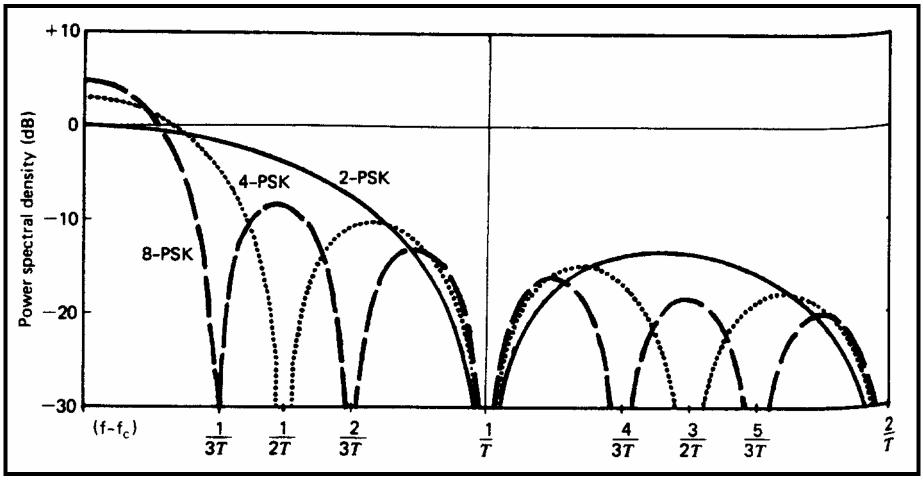


The resultant BPSK spectrum is:



A more comprehensive sketch of the power spectral density as a function of phase states is given by:

PSK Spectra[1]



5.1.2 QPSK Modulators [4-PSK]

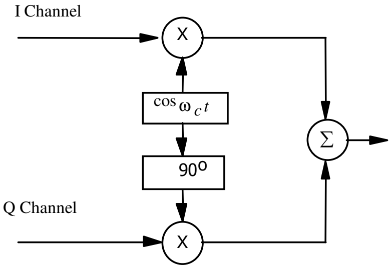
[QPSK System using Ideal Components by Elanix]

[QPSK System using Baseband Processing by Elanix]

[QPSK System using Real Components by Elanix]

Quadrature modulation uses two data channels denoted I† and Q† displaced by 90º with respect to each other. It may seem somewhat paradoxical, that although these two channels are combined prior to transmission, they do not interfere with each other.

Quadrature (or Vector) Modulator



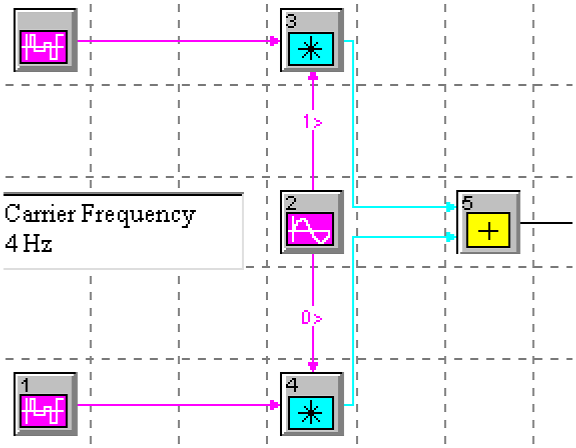
---

[1] *Digital Telephony* (2nd ed.), John Bellamy, Figure 6.15

† In phase

† Quadrature phase

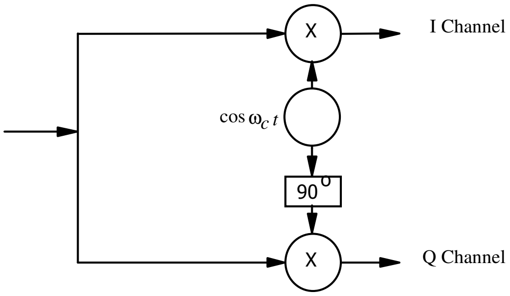
SystemView Vector Modulator



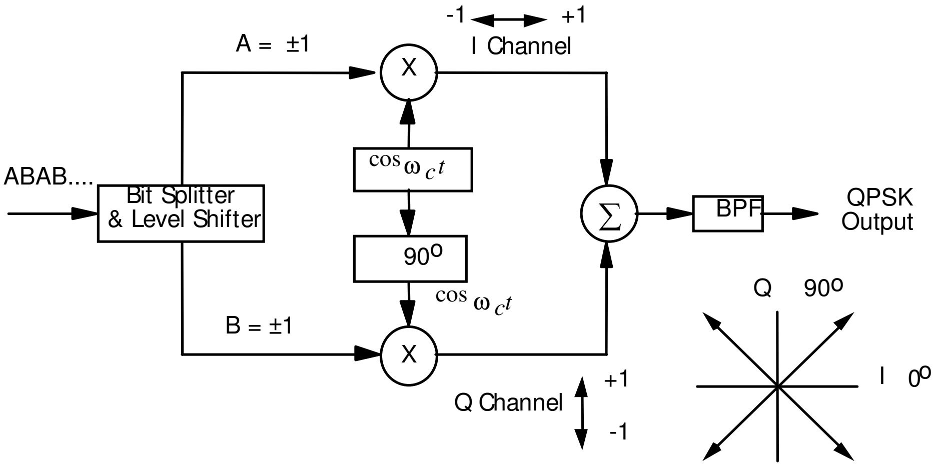
The receiver is quite capable of separating them because of their quadrature or orthogonal nature.

Quadrature Demodulator

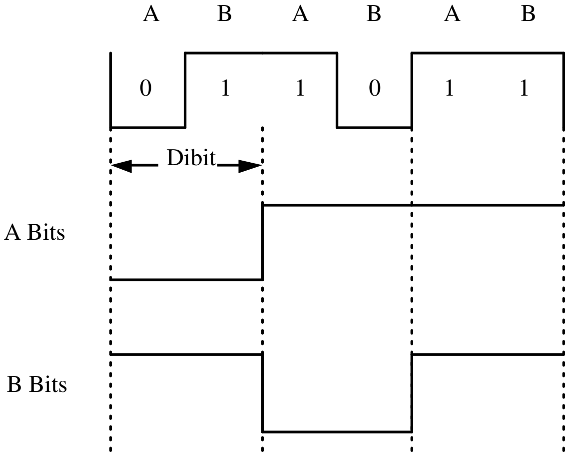
[Quadrature Demodulator by Elanix]



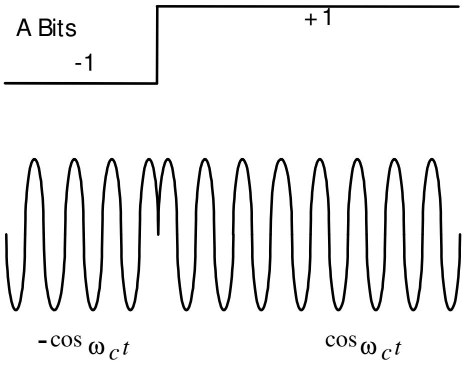
In the most basic configuration, there are 4 possible output phases. This suggests that each output symbol correspond to 2 bits of binary information. Since several bits can be encoded into a baud, the bit rate exceeds the baud rate.



The first thing that happens in this circuit is that the incoming bits are organized into groups of 2 called dibits. They are separated into 2 data streams and kept constant over the dibit period.

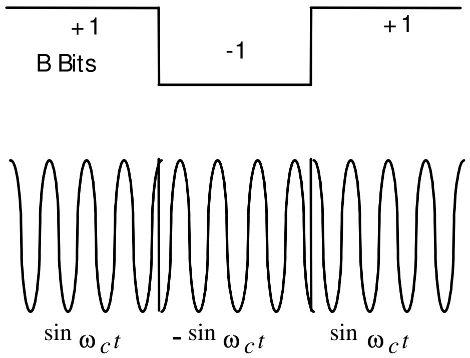


Each data stream is fed to a BPSK modulator. However, orthogonal carriers feed the two modulators. The output of the I channel modulator resembles:



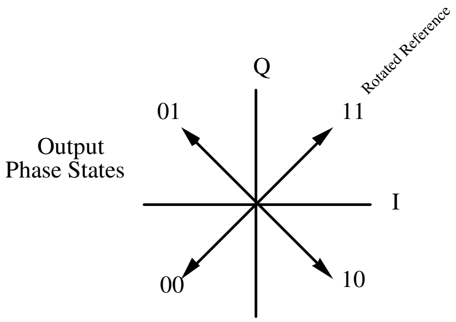
Output of I Channel Modulator

The output of the Q channel modulator resembles

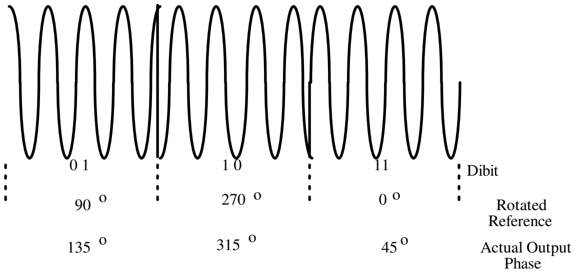


Output of Q Channel Modulator

Combining the I and Q channels has the effect of rotating the output state by 45°.



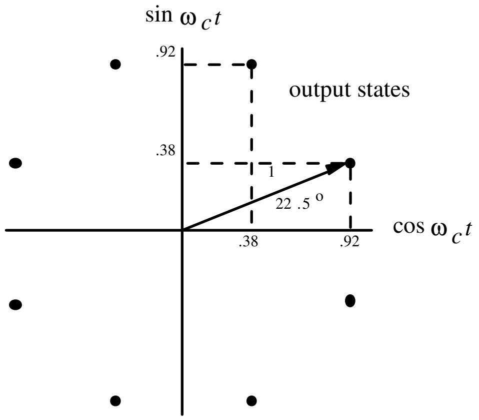
Rotating the output reference to 45° for the sake of clarity, the transmitted output for this particular data sequence is therefor:



5.1.3 8-PSK

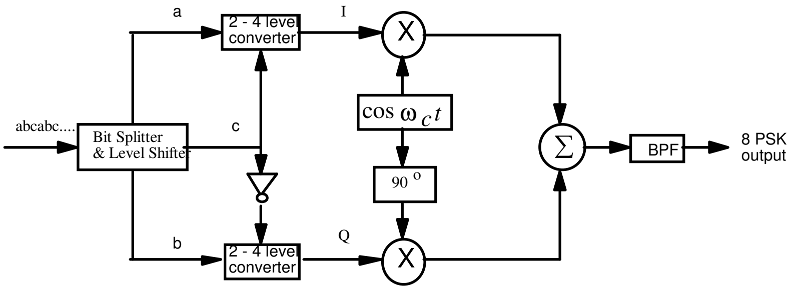
This process of encoding more bits into each output baud or phase state can be continued. Organizing binary bits into 3 bytes corresponds to 8 different conditions.

The output constellation diagram for the 8 different phase states is:



From this diagram it is readily apparent that two different amplitudes are needed on the I and Q channels. If the A bit is used to control the polarity of the I channel and the B bit the polarity of the Q channel, then the C bit can be used to define the two different amplitudes. In order to evenly space the phase states; the amplitudes must be ± 0.38 and ± 0.92. The magnitude of the I and Q channel signals must always be different. An inverter can be used to assure this condition.

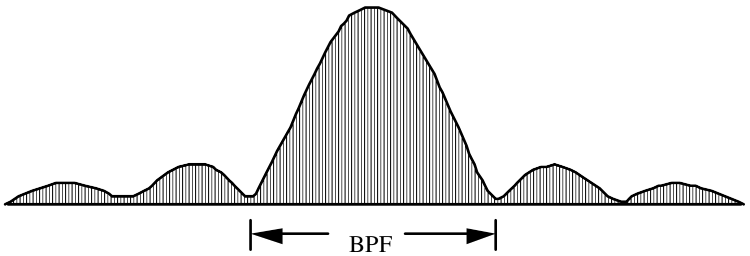
The input bit stream is organized into 3 bit bytes. Each bit is sent to a different location to control a certain aspect of the modulator. The inputs to the 2 - 4 level converter are 0’s or 1’s but the output is ± 0.38 or ± 0.92, depending on the C bit.



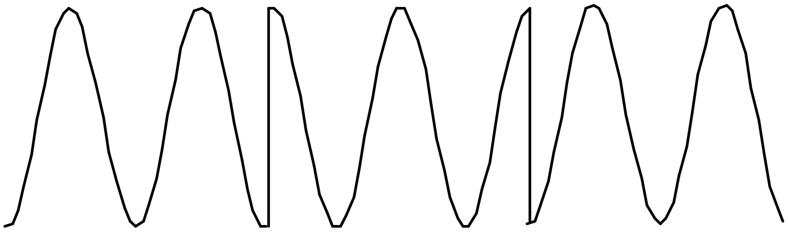
5.1.3.1 Continuous PSK

Phase transitions give rise to high frequency components in the transmitted spectrum. Consequently, a BPF is placed at the output in order to pass only the main spectral lobe. This creates smooth rather than abrupt phase transitions, which in turn gives rise to amplitude variations.

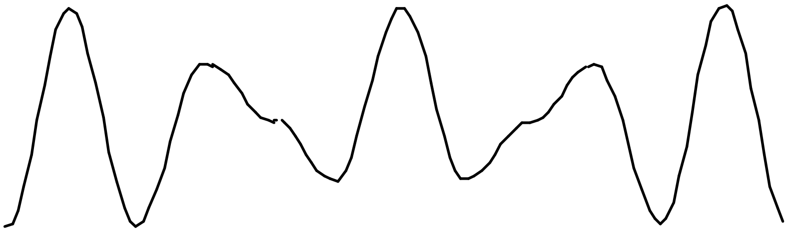
The unfiltered spectrum may resemble:



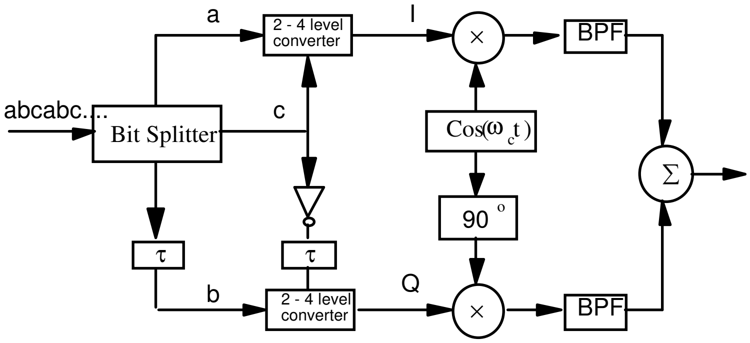
Before the bandpass filter, the phase-shifted signal may appear as:



But after the bandpass filter, it is somewhat altered. Note that undesirable amplitude variations have occurred.



There is no particular reason why the BPF has to be placed at the output. If it were placed in the I and Q paths, which were offset by half a bit period from each other, then the final output variations would be significantly reduced.



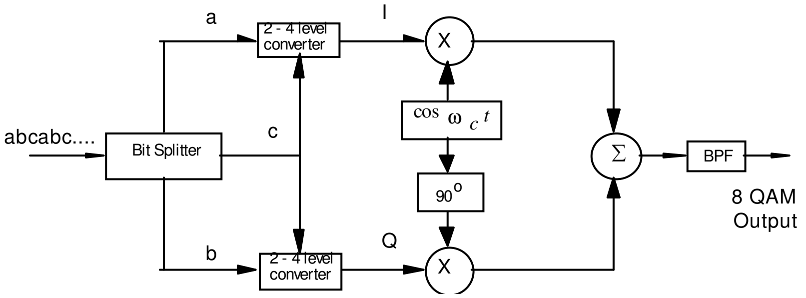
5.1.4 π/4 QPSK

5.2 Quadrature Amplitude Modulation

To increase the modulation efficiency the signal amplitude can also be varied in conjunction with phase modulation. The signal amplitude can take many states, but the current practical limit is 64.

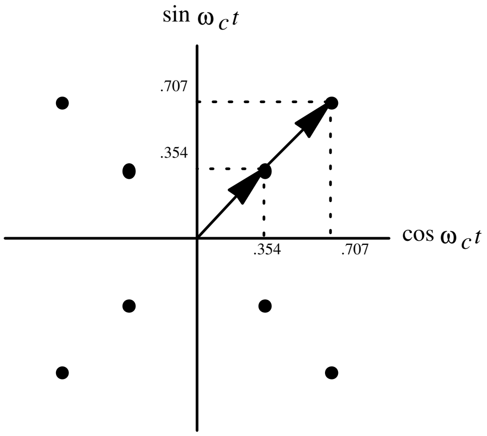
5.2.1 8-QAM

An 8 state device can have 2 different amplitude possibilities for each of 4 possible output phases. For simplicity, we'll select a bi-level system with amplitudes of 1 & 0.5.

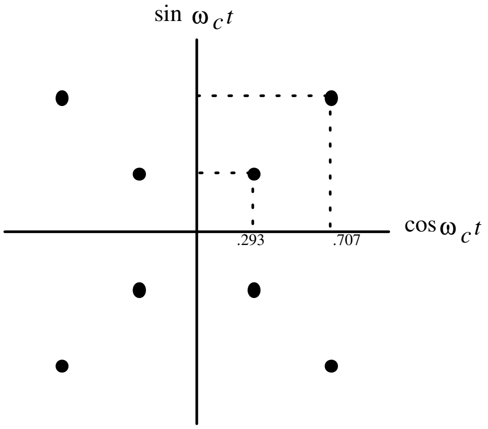


The a & b bits control the polarity in their respective channels, while the c bit governs the two possible amplitudes [Note: 0.5xSin(45°) = 0.354 and 1xSin(45°) = 0.707]

The constellation diagram for this system is:

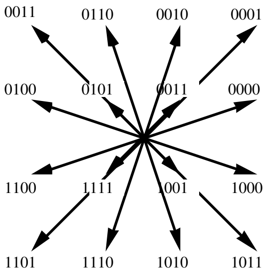


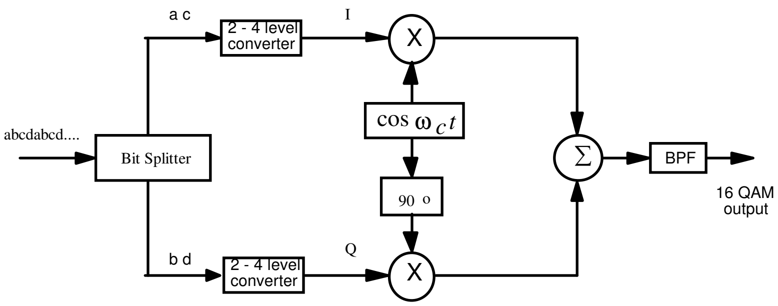
A slight improvement can be made to this example, by evenly spacing the data points [and therefor making all of the eye openings equal], as follows:



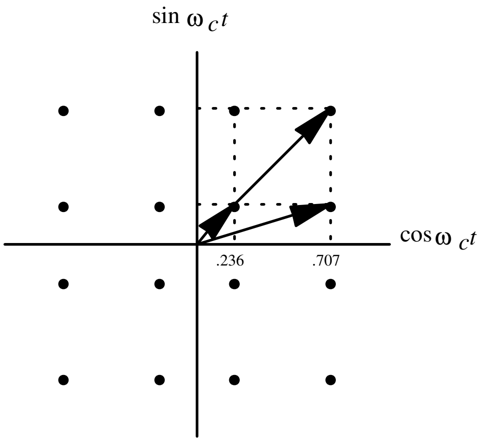
5.2.2 16-QAM

This system uses 12 phases and 3 different amplitudes to produce 16 states. It requires D1 conditioning on 4 wire private lines to provide 9600 bps full duplex operation.



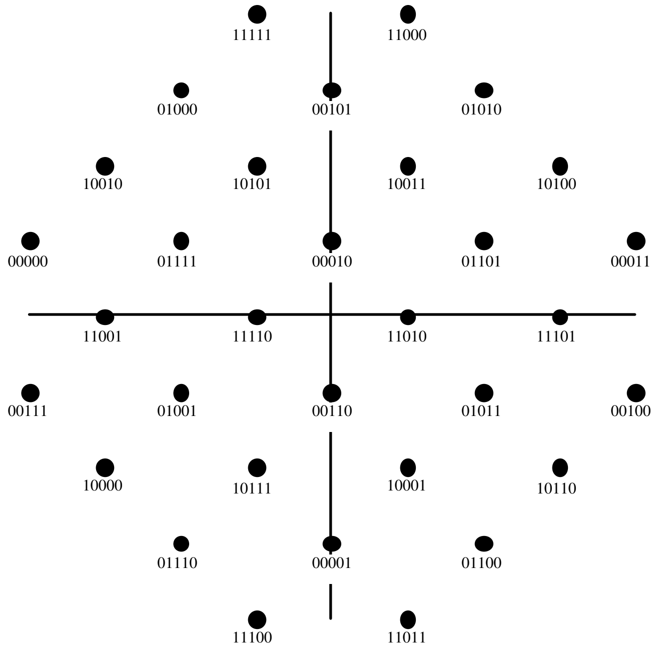


One possibility is to let the a and b bits control the polarity, and the c and d bits control the 2-4 level converter output amplitude. For the sake of comparisons, the maximum QAM output amplitude has again been fixed at 1.



5.2.3 32 QAM

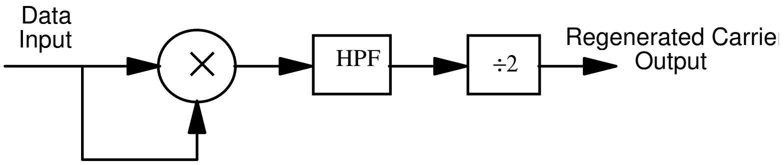
The output constellation diagram resembles:



5.3 Carrier Recovery Techniques

Modems utilizing phase modulation must regenerate the carrier signal before the phase of the input signal can be determined. One way to regenerate the carrier is to use a squaring loop.

5.3.1 Squaring Loop



SystemView Model

To verify that this circuit recreates the carrier, we simply apply all the possible input signals and observe what happens at the output.

Case I - assume a BPSK input

$$\text{input} \quad = \pm\cos(\omega_i t)$$

$$\begin{aligned}\text{multiplier output} &= [\pm\cos(\omega_i t)][\pm\cos(\omega_i t)] \\ &= \frac{1}{2}\cos(\omega_i t - \omega_i t) + \frac{1}{2}\cos(\omega_i t + \omega_i t) \\ &= \frac{1}{2} + \frac{1}{2}\cos(2\omega_i t)\end{aligned}$$

After the HPF we obtain: $\frac{1}{2}\cos(2\omega_i t)$

After the divider we obtain: $\frac{1}{2}\cos(\omega_i t)$

This carrier signal is now independent of the data signal.

Case II - assume a 4-PSK input

$$\begin{aligned}\text{input} &= \pm\sin(\omega_i t) \pm \cos(\omega_i t) \\ \text{or} &= \pm\cos\left(\omega_i t \pm \frac{\pi}{2}\right)\end{aligned}$$

$$\begin{aligned}\text{multiplier output} &= \left[\pm\cos\left(\omega_i t \pm \frac{\pi}{2}\right)\right]\left[\pm\cos\left(\omega_i t \pm \frac{\pi}{2}\right)\right] \\ &= \frac{1}{2}\cos\left(\omega_i t \pm \frac{\pi}{2} - \omega_i t \mp \frac{\pi}{2}\right) + \frac{1}{2}\cos\left(\omega_i t \pm \frac{\pi}{2} - \omega_i t \pm \frac{\pi}{2}\right) \\ &= \frac{1}{2} + \frac{1}{2}\cos(2\omega_i t \pm \pi)\end{aligned}$$

After the HPF we obtain: $\frac{1}{2}\cos(2\omega_i t \pm \pi)$

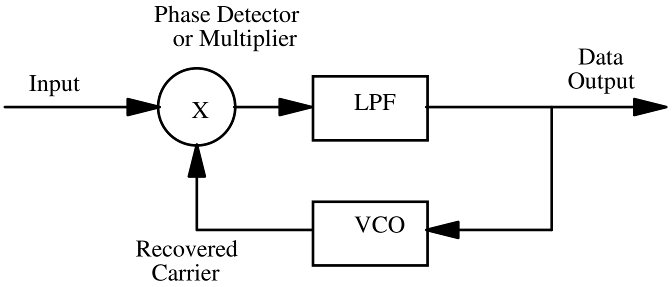
The sign inversion in front of π is of no consequence since cosine is an even function.

After the divider we obtain: $\frac{1}{2}\cos\left(\omega_i t \pm \frac{\pi}{2}\right)$

Again, this is a carrier signal independent of the data signal.

5.3.2 Phase Locked Loop (Linearized)

A second way to regenerate a carrier is to use a PLL. These loops can be either digital or analog in nature. Their operation is easiest to analyze when they are composed of linear analog circuits. This method is usable with FSK, PSK and QAM based modems.



$$\text{let the input } = \sin(\omega_i t)$$

$$\text{let the VCO output } = \cos(\omega_o t + \theta)$$

Then the multiplier output is:

$$\sin(\omega_i t)\cos(\omega_o t + \theta) = \frac{1}{2}\sin(\omega_i t + \omega_o t + \theta) + \frac{1}{2}\sin(\omega_i t - \omega_o t - \theta)$$

After the LPF we obtain:

$$\frac{1}{2}\sin(\omega_i t - \omega_o t - \theta)$$

If $\omega_i \neq \omega_o$ then θ is irrelevant and the circuit is not in lock.

However, if

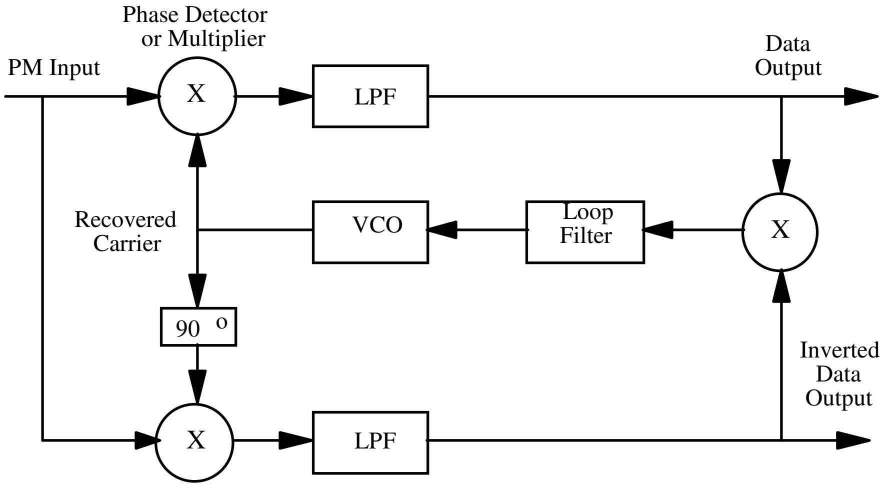
$$\omega_i > \omega_o \text{ the output is positive}$$

$$\omega_i < \omega_o \text{ the output is negative}$$

Therefor this signal can be used to drive the VCO in such a way that it will force $\omega_i = \omega_o$. This is the frequency locked state.

When $\omega_i = \omega_o$, then the output of the LPF is $\frac{1}{2}\sin(-\theta)$, where θ is the phase difference between the input and VCO output. Since this term is an odd function, it can be used to drive the VCO such that phase lock is maintained. Note that the zero error signal occurs when the input and VCO output are in phase quadrature.

5.3.3 Costas Loop (Linearized)



This circuit will acquire lock in exactly the same manner as the standard PLL.

Assume a BPSK input and that the circuit is initially in the unlocked state:

$$\begin{aligned}
\text{Input} &= \pm\sin(\omega_i t) \\
\text{VCO output} &= \cos(\omega_o t) \\
\text{Top Multiplier Output} &= \tfrac{1}{2}\sin(\omega_i t+\omega_o t)+\tfrac{1}{2}\sin(\omega_i t-\omega_o t) \\
\text{After the LPF} &= \tfrac{1}{2}\sin(\omega_i t-\omega_o t) \\
\text{Bottom Multiplier Output} &= -\tfrac{1}{2}\cos(\omega_i t+\omega_o t)+\tfrac{1}{2}\cos(\omega_i t-\omega_o t) \\
\text{After the LPF} &= \tfrac{1}{2}\cos(\omega_i t-\omega_o t)
\end{aligned}$$

If we allow either the filters or multipliers to have gain, we can bring the amplitudes back up to unity.

The output of the right hand multiplier will then be:

$$\sin(\omega_i t-\omega_o t)\cos(\omega_i t-\omega_o t)=\tfrac{1}{2}\sin\left(2\{\omega_i-\omega_o\}t\right)$$

This is produces an error voltage proportional to 2 times the difference frequency, and is used to drive the VCO in the same manner as a standard PLL.

Once frequency lock is achieved and $\omega_i = \omega_o$, then:

$$\begin{aligned}
\text{Input } &= \pm\sin(\omega_i t) \\
\text{VCO output } &= \cos(\omega_i t + \theta) \\
\text{Top Multiplier Output } &= \sin(\omega_i t + \omega_i t + \theta) + \tfrac{1}{2}\sin(\omega_i t - \omega_i t - \theta) \\
\text{After the LPF } &= \sin(-\theta) \\
\text{Bottom Multiplier Output } &= \cos(\omega_i t + \omega_i t + \theta) + \tfrac{1}{2}\cos(\omega_i t - \omega_i t - \theta) \\
\text{After the LPF } &= \tfrac{1}{2}\cos(-\theta)
\end{aligned}$$

The output of the right hand multiplier will then be of the form:

$$\sin(-\theta)\cos(-\theta) = \tfrac{1}{2}\sin(-2\theta)$$

An error signal proportional to 2 times the phase angle difference is created. This implies that the data is therefor decoded.

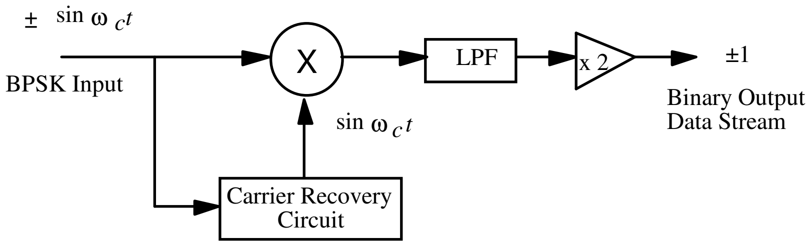
Note however that this function is now cyclic and the Costas loop may lock into 1 of 2 possible states. Consequently, data may appear in either output. For this reason, differential encoding of the data must be employed.

If one injects a 4-PSK signal, the results are the same.

5.4 Demodulation Techniques

5.4.1 BPSK Demodulator

Demodulation is slightly more complex since the receiver must have two signals present before it can make a phase comparison or measurement. One of the two signals required is naturally the input signal itself. The other is a reconstructed reference carrier. These two signals can be fed through a phase comparitor, which in its simplest form is a multiplier.



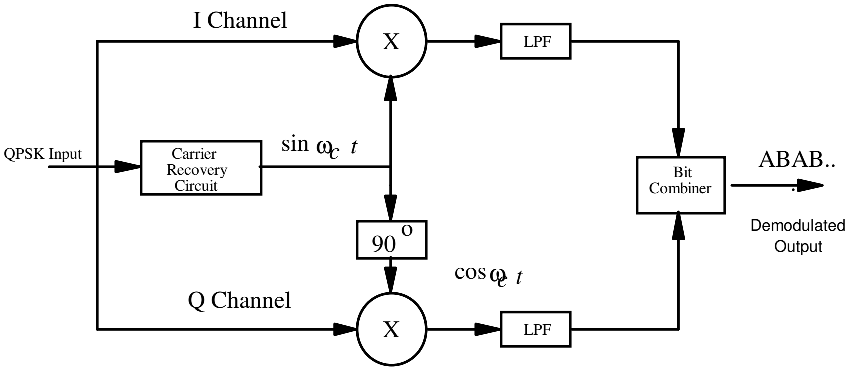
The signal appearing out of the multiplier is:

$$\pm\sin(\omega_c t)\sin(\omega_c t) = \pm\frac{1}{2}\left[1 - \cos(2\omega_c t)\right]$$

After the LPF, we obtain: $\pm\frac{1}{2}$, and after the amplifier [with a gain of 2], we obtain: ±1. This corresponds to the original binary data input.

5.4.2 4-PSK Demodulator

The demodulator circuit must regenerate a reference carrier to decode the phase modulation.



There are 4 possible input states: $\pm\sin(\omega_c t)\pm\cos(\omega_c t)$

The I channel multiplier output is given by:

$$
\begin{aligned}
&[\pm\sin(\omega_c t)\pm\cos(\omega_c t)]\sin(\omega_c t)\\
&=\pm\left[\tfrac{1}{2}\cos(\omega_c t-\omega_c t)-\tfrac{1}{2}\cos(\omega_c t+\omega_c t)\right]\pm\left[\tfrac{1}{2}\sin(\omega_c t-\omega_c t)+\tfrac{1}{2}\sin(\omega_c t+\omega_c t)\right]\\
&=\pm\left[\tfrac{1}{2}-\tfrac{1}{2}\cos(2\omega_c t)\right]\pm\left[\tfrac{1}{2}\sin(2\omega_c t)+0\right]
\end{aligned}
$$

After the LPF, we obtain: $\pm\frac{1}{2}$ Note that this value occurs because of the product of:

$$\pm\sin(\omega_c t)\sin(\omega_c t)$$

Therefor, we have successfully decoded the original data I channel. Similar results are obtained for the Q channel:

$$
\begin{aligned}
&[\pm\sin(\omega_c t)\pm\cos(\omega_c t)]\cos(\omega_c t)\\
&=\pm\left[\tfrac{1}{2}\sin(\omega_c t+\omega_c t)-\tfrac{1}{2}\sin(\omega_c t-\omega_c t)\right]\pm\left[\tfrac{1}{2}\cos(\omega_c t-\omega_c t)+\tfrac{1}{2}\cos(\omega_c t+\omega_c t)\right]\\
&=\pm\left[\sin(2\omega_c t)-0\right]\pm\left[\tfrac{1}{2}+\tfrac{1}{2}\cos(2\omega_c t)\right]
\end{aligned}
$$

After the LPF, we obtain: $\pm\frac{1}{2}$ Note that this bit value occurs because of the product:

$$\pm\cos(\omega_c t)\cos(\omega_c t)$$

Therefor, again we have successfully decoded the original Q channel.

_____ Notes _____

Review Questions

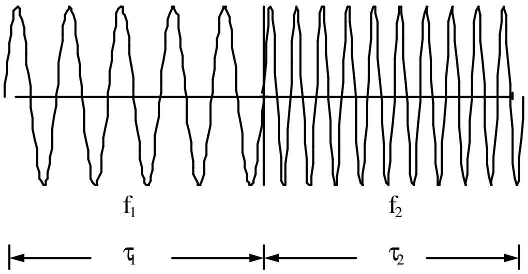
Quick Quiz

1. The [DTE, DCE] is the source of information.
2. A simplex connection takes [a greater, the same, a lesser] number of wires than a half-duplex connection.
3. Most modems transmit [asynchronous, synchronous] data.
4. Null modems do not require a power source. [True, False]
5. The simplest modulation technique, OOK, is also known as [ASK, PSK]
6. In an FSK modem, the duration of the tone burst corresponds to the baud. [True, False]
7. Caller ID messaging follows the Bell [202, 204] standard and employs [BPSK, BFSK] modulation.
8. No version of the 202 series modem uses two loops. [True, False]
9. Higher bit rates are achieved over [simplex, full duplex] FSK modems.
10. A dibit is a group of two bits. [True, False]
11. Combining the I and Q channels in a PSK modem, effectively shifts the output phase by 45^o. [True, False]
12. The DTE data stream in an 8 PSK modem is broken up into 3 streams internally. [True, False]
13. Continuous PSK requires that one of the quadrature channels be delayed by [one half, one, two] bit period(s).
14. In order to increase the bit rate of PSK modems, some form of amplitude modulation is required. [True, False]
15. The full potential of 56K modems can be used between two users connected to analog loops. {True, False]

Analytical Problems

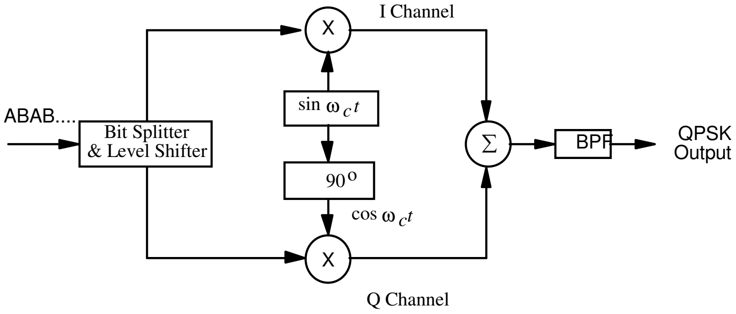
1. Stating any and all assumptions, prove that a Costas loop is a 4-PSK demodulator.
2. Sketch the approximate spectrum of an FSK signal where:
    - f_1 = 1000 Hz

- $f_2 = 2000$ Hz
- $\tau_1 = \tau_2 = 5$ mSec.



Verify your results by means of a SystemView simulation.

3. Stating any and all assumptions, show mathematically that the following circuit is a QPSK modulator:



Composition Questions

1. List the three basic modulation schemes used by modems over telephone lines.
2. Name three carrier recovery techniques used in DCEs.
3. Define baud.
4. What is the purpose of a secondary channel on a modem?
5. Sketch the block diagram and constellation diagram of a 16 QAM modulator and discuss its operation.

Notes

For Further Research

Alisouskas Vincent F & Tomasi Wayne, *Digital and Data Communications*, Prentice-Hall, 1985

Bigelow Stephen J, *Understanding Telephone Electronics* 3rd ed., SAMS, 1991

Bigelow Stephen J, Modem Communications Standards, Electronics Now, September 1994

Campbell Joe, *The RS-232 Solution*, Sybex, Berkley, 1984

Killen Harold B, *Telecommunications and Data Communication System Design with Troubleshooting*, Prentice-Hall, 1986

Schneider Dr. Kenneth S, *Primer on Premises Data Communication*, Telebyte Technologies

Sinnema William, *Digital, Analog, and Data Communication*, Reston, 1982

Tugal Dougan A & Tugal Osman, *Data Transmission: Analysis Design Application* 2nd ed., McGraw-Hill, 1989

Digital Modulation in Communications Systems – An Introduction, Hewlett Packard, Application Note 1298

Modems

http://www.taxpolicy.com/tutorial/modtutor.htm

http://web.syr.edu/~jmwobus/dialups/

http://www.teleport.com/~curt/modems.html

http://www.sfn.saskatoon.sk.ca/Help/ModemTutorial/ModemTutorial.html

http://www.bpa.nl/pcmntt/cyberp/index/Modem.html

http://cctpwww.cityu.edu.hk/network/l3_modem.htm

Cable Modems

http://www.cabledatacomnews.com/cmic1.htm

56K Modems

www.3com.com

www.nb.rockwell.com

http://www.56k.com/

http://www.mot.com/MIMS/ISG/Papers/56k_wp.html

http://www.lucent.com/micro/K56flex/

http://x2.usr.com/technology/faqs.html

V.90

http://www.nb.rockwell.com/K56flex/index.html

http://www.v80.com/

Networking

http://nsrc.org/index.html

Tutorial

http://www.physics.udel.edu/wwwusers/watson/student_projects/scen167/thosguys/index.html

Journals

http://www.micronpc.com/support/links/publink1.html