## Chapter Contents

# 5.0 Modems

## Objectives

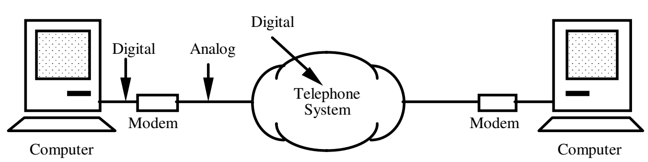
This section will:

- Summarize the various modem standards
- Examine the RS-232 interface
- Review the basic ASK, FSK, and PSK modulation schemes
- Examine the various QAM modulators
- Examine the various ways to recover the carrier
- Examine 56K modem operation

The following article published by Hewlett Packard is essential reading:

Digital Modulation by Hewlett Packard

A **modem**† allows digital information to be passed through an analog transmission facility by modulating carrier signals within the network passband. This can be done by using amplitude, frequency, and phase modulation or some combination. The device at which the digital information begins and ends its journey is called a **DTE**†. The modem is generically referred to as the **DCE**†.




Modems can be characterized by their speed, modulation technique or transmission mode. The four basic transmission modes are:

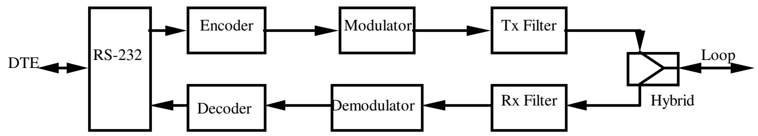
- Simplex: able to transmit or receive
- Half duplex: able to transmit and receive but not simultaneously
- Full duplex: able to transmit and receive simultaneously over a single loop
- Full-full duplex: able to transmit and receive simultaneously over two loops

† MODulator DEModulator

† Data Terminal Equipment

† Data Communications Equipment

Basic Modem Block Diagram




Most modems transmit data asynchronously. That is they add start and stop bits to each data byte. Some more expensive modems transmit information synchronously.

At one time, AT&T's Bell Labs dominated the communications industry. As a result, the equipment it created had a tendency to establish de facto standards. Bell modem numbers are still used to classify many types of DCE.

## 5.1 RS-232 C Interface

RS-232 Standard

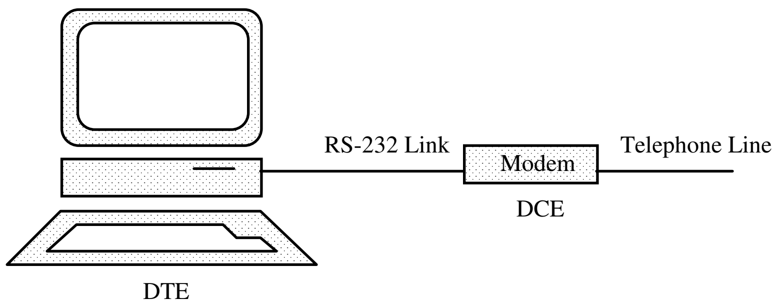
RS-232 Tutorial

http://www.airborn.com.au/rs232.html

http://www.sangoma.com/signal.htm

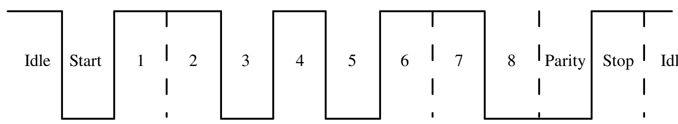
http://www.rs485.com/rs485spec.html

A very common way to interconnect DTEs and DCEs is by a digital link such as RS-232. This link contains a number of control signals in addition to the data signal.




Inside a computer, data is handled in a parallel fashion. To get out of the computer it first passes through a UART that converts it to a serial stream and out the serial port to the DCE. Some computers have modems built into them. Consequently, there may be internal hardware conflicts, in which case the external serial port has to be disabled.

An asynchronous modem adds start, parity and stop bits to each character in the serial string before transmission. This constitutes a data frame.



The idle state is always taken as a high, and start is active low. There can be anywhere from 5 to 8 data bits in a frame, but most BBS networks use 7 or 8 bits.

Since parity bits are ineffective for detecting more than a one-bit error, the communications software often sets the parity to *none*. However, if it is used, even parity means that the parity bit is set to a logical one if there is an even number of bits in the data word. Odd parity is the reverse.

Two modems must use the same type of frame in order to communicate. Most BBS networks use: 8 data bits, no parity, and one stop bit. This is sometime written as 8, N, 1. Another popular arrangement is 7, E, 1.

The RS-232 is widely used to interconnect devices located within 15 meters of each other. Longer distances can be achieved, but at lower bit rates.

| | |
|---|---|
| Standard bearer: | EIA |
| European equivalent: | V.24 and V.28 |
| Typical 1 level: | -5 to -15 volts |
| Typical 0 level: | 5 to 15 volts |
| Maximum bit rate: | 19.2 Kbps [this original limitation has now been exceeded] |

_____ Notes _____

### 5.1.1 RS-232 DCE Connector

| Pin | Mnemonic | Interchange Circuit | To DCE | From DCE | Comments |
|---|---|---|---|---|---|
| 1 | PG | AA | | | Chassis Ground |
| 2 | TD | BA | √ | | Transmit DATA |
| 3 | RD | BB | | √ | Received DATA |
| 4 | RTS | CA | √ | | Request to Send |
| 5 | CTS | CB | | √ | Clear to Send |
| 6 | DSR | CC | | √ | Data Set Ready |
| 7 | SG | AB | | | Signal Ground |
| 8 | DCD | CF | | √ | Carrier Detect |
| 9 | | | | | |
| 10 | | | | | |
| 11 | | | | | |
| 12 | (S)DCD | SCF | | √ | Secondary Received Sig Det |
| 13 | (S)CTS | SCB | | √ | Secondary Clear to Send |
| 14 | (S)TD | SBA | √ | | Secondary Transmit DATA |
| 15 | TSET | DB | | √ | DCE Timing |
| 16 | (S)RD | SBB | | √ | Secondary Received DATA |
| 17 | RSET | DD | | √ | DCE Receiver Timing |
| 18 | | | | | |
| 19 | (S)RTS | SCA | √ | | Secondary Request to Send |
| 20 | DTR | CD | √ | | Data Terminal Ready |
| 21 | SQ | CG | | √ | Signal Quality Detector |
| 22 | RI | CE | | √ | Ring Indicator |
| 23 | | CH/CI | √ | √ | Data Signaling Rate Selector |
| 24 | TSET | DA | √ | | DTE Transmitter Timing |
| 25 | | | | | |

Interchange Circuit Category

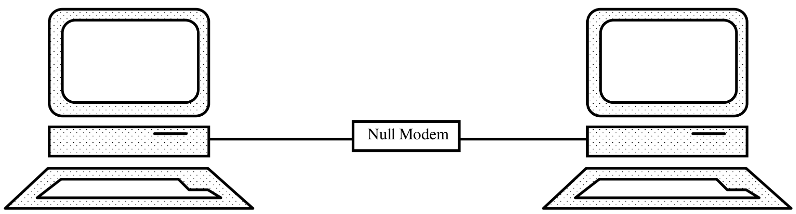
| | |
|---|---|
| A | Ground |
| B | Data |
| C | Control |
| D | Timing |
| S | Secondary |

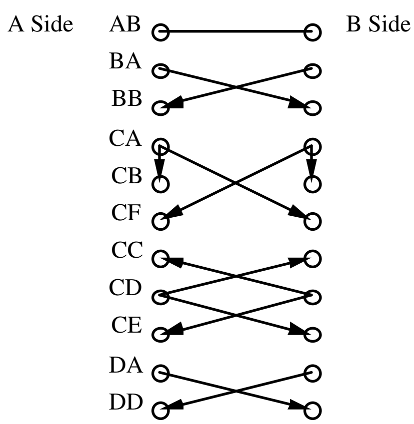
9 Pin Serial Port Assignments

| Pin | Nomenclature | Comment |
|---|---|---|
| 1 | DCD | Data Carrier Detect |
| 2 | TX | Transmit Data |
| 3 | RX | Receive Data |
| 4 | DTR | Data Terminal Ready |
| 5 | GND | Signal Ground |
| 6 | DSR | Data Set Ready |
| 7 | RTS | Request to Send |
| 8 | CTS | Clear to Send |
| 9 | RI | Ring Indicator |

### 5.1.2 Null Modems

Two computers equipped with RS-232 interfaces can be directly connected by a null modem or no modem cable adapter. This unit reverses the connections on pins such as 2 and 3 to allow the DTEs to communicate without the need of a modem.



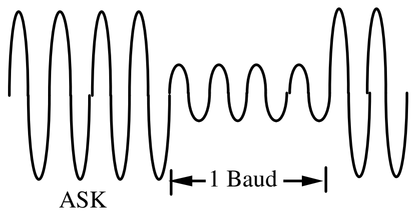



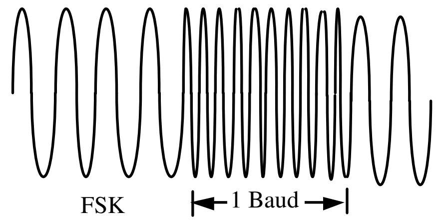

Null Modem

## 5.2 Modulation Techniques

All forms of modulation create sidebands comprised of sum and difference frequencies of the data signal and carrier. It is necessary that the resultant spectrum stay within the bandwidth confines of the transmission channel. In the case of the switched PSTN the bandwidth channel is 300 Hz to 3400 Hz. In spite of this severe limitation, it is possible to up to 56 Kbps though the network.

This brings up the subject of bauds. The baud is defined as the shortest signaling element on the loop, and the baud rate is its reciprocal. It may be that the bit rate and baud rates are the same, but in order to achieve high throughput, they are not. The bit rate is inevitably higher than the baud rate. The highest baud rate possible on a standard phone line is about 2400 baud. By encoding 2 bits in every baud, 4800 bps is obtained. By encoding 4 bits in every baud, 9600 bps is obtained, and so on.




## 5.2 Amplitude Modulation

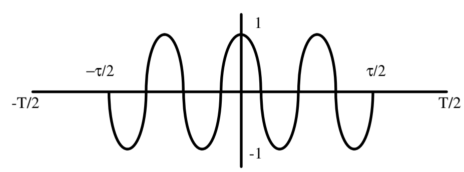
http://www.educatorscorner.com/experiments/spectral/SpecAn5.shtml

http://robotics.eecs.berkeley.edu/~sastry/ee20/modulation/node1.html

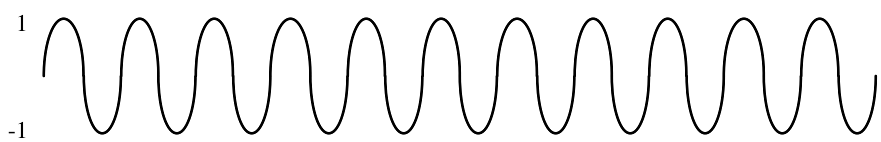
**ASK**† or **OOK**† is the simplest form of amplitude modulation and is accomplished by turning a carrier on and off. Arbitrarily, one of the amplitude values can be zero. This form of modulation can also be considered as a special case of frequency modulation since the output consists of frequency bursts.

The spectral content, of a frequency burst can be determined analytically by means Fourier Transform, or intuitively by decomposing the signal into its basic components.

By decomposition, the following ASK signal:



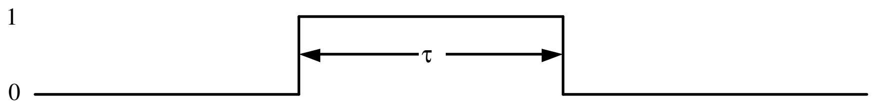

is actually made up of two time domain components, a constant amplitude tone:



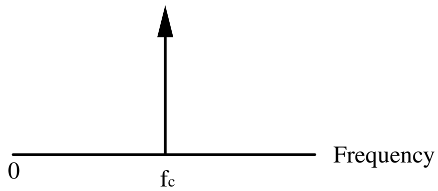

and a gating pulse:

† Amplitude Shift Keying

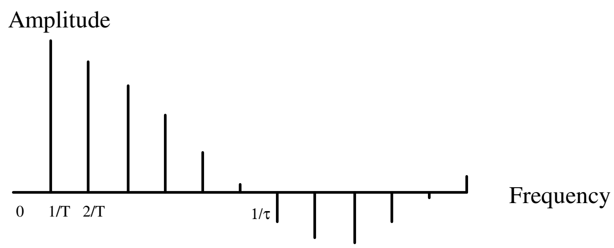
† On Off Keying



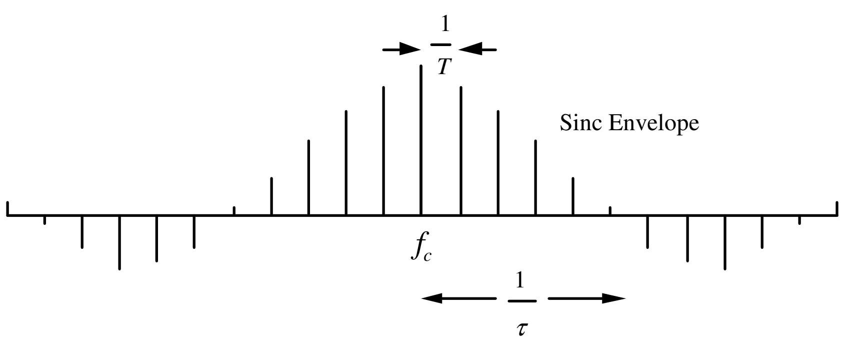

The gating pulse is used to enable and disable the tone. In the frequency domain, the tone signals is represented by:




In the frequency domain, the gating pulse is represented by:




If these two signals are multiplied together, we obtain the frequency burst. The spectra of these two signals are easily determined. The product of trigonometric functions corresponds to the sum and difference of the angles or angular velocities. This corresponds to sum and difference frequencies, and creates the following spectrum:




The total signal bandwidth is usually described as the portion between the first two nulls.

$$\text{Bandwidth} \quad = f_c + \frac{1}{\tau} - \left( f_c - \frac{1}{\tau} \right) = \frac{2}{\tau} \quad \text{Hz}$$

This method of using ASK can be expanded to include any number of amplitude levels.

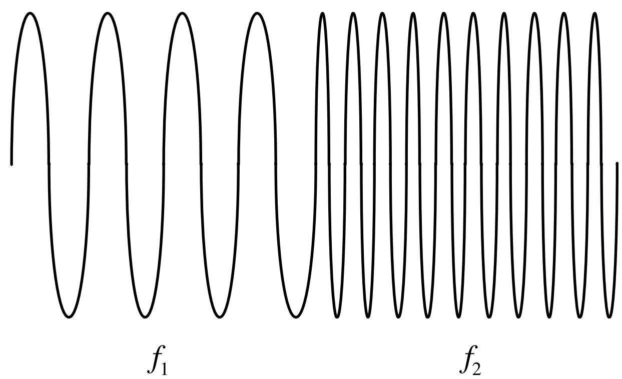
SystemView BY ELANIX

## 5.4 Frequency Modulation

A BFSK System - Part 1 by Elanix

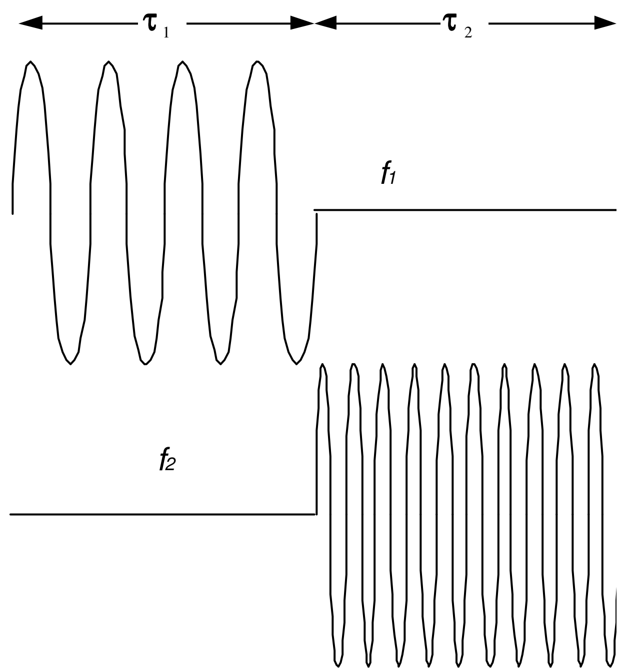
A BFSK System - Part 2 by Elanix

In an FSK modem, the mark and space are distinguished by two different frequencies:

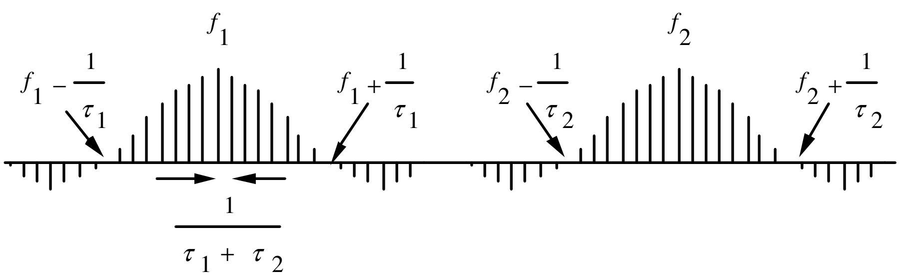



The time of duration of each tone burst corresponds to a baud, since the tone burst forms the basic signaling element. In the above system, the baud and bit rates are equal.

A FSK signal may be decomposed into two time displaced ASK bursts:




In the frequency domain, the spectrum of this signal appear as:




The bandwidth of this spectrum is defined as:

$$\text{Bandwidth} \quad = f_2 + \frac{1}{\tau_2} - \left( f_1 - \frac{1}{\tau_1} \right) = f_2 - f_1 + \frac{\tau_1 + \tau_2}{\tau_1 \tau_2} \quad \text{Hz}$$

$$\text{if} \quad \tau_1 = \tau_2 = \tau$$

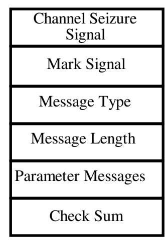
$$\text{then} \quad \text{Bandwidth} \quad = f_1 - f_2 + \frac{2}{\tau}$$

### 5.4.1 Half Duplex FSK Modems

The 202 modem is used in North America and the V.23 is used in Europe. It might seem that these devices would find no application in modern communications systems because of their limited capabilities, but this is not quite the case. Some applications do not require high performance.

One popular application is caller ID, where the calling party's name or telephone number is displayed. The display information is sent as continuos phase BFSK tones during the 4-second silent interval between the first and second ring.

These messages can even be sent while the line is occupied, if call waiting is supported. The message structure is of the form:

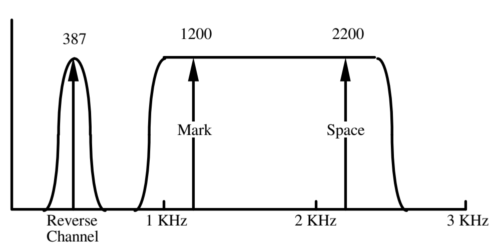



Each one of these data fields has a unique purpose:

- Channel seizure signal: This is used for on-hook data only. It consists of a series of 300 alternating 1s and 0s, starting with o and ending with 1.
- Mark signal: This is 80±10 bits of continuous high.
- Message type: An 8-bit byte.
- Message length: A 1-byte word specifying the length of the subsequent message.
- Parameter message: Each of *N* parameters are broken down into 3 sub-fields: parameter type, length, and data. Some of the data that is included may be date, time, incoming call number, reason for absence of call number.
- Check sum: This is a 1-byte 2's complement sum of fields 3, 4, and 5, mod 256.

### 5.4.2 202 Modem

The S version of this device works over the standard single twisted pair telephone loop. The T version offers full duplex capabilities but requires two loops.

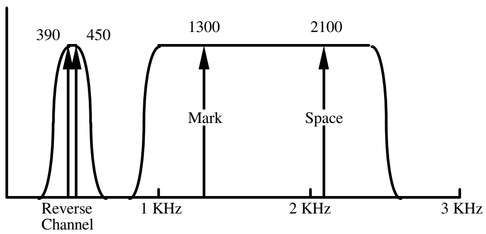


Notes

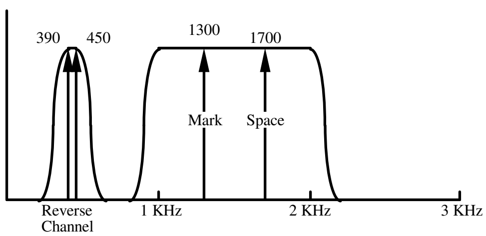
| | |
|---|---|
| Maximum bit rate | 1200 bps |
| Mark/space frequencies | 1200/2200 Hz |
| Signaling channel | 5 bps at 387 Hz |

## 5.4.3 1200 Baud V.23 Channel

This system uses a 75-baud FSK reverse channel.




## 5.4.4 1600 Baud V.23 Channel



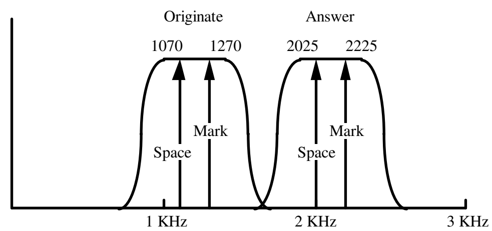

## 5.4.5 Full Duplex FSK Modems

The full duplex capability of these modems is achieved by lowering the baud rate.

### 103 Modem

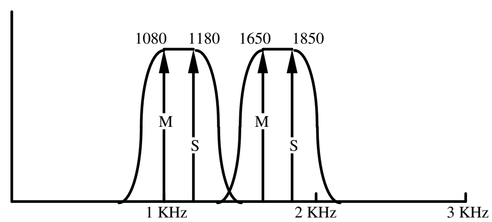
This asynchronous full duplex device can configure itself into either originator or answer modes. In the idle state, the modem is in the answer mode.

______ Notes ______




| | |
|---|---|
| Maximum bit rate | 300 bps |
| Originate m/s frequencies | 1270/1070 Hz |
| Answer m/s frequencies | 2225/2025 Hz |

300 Baud V.21 Channel

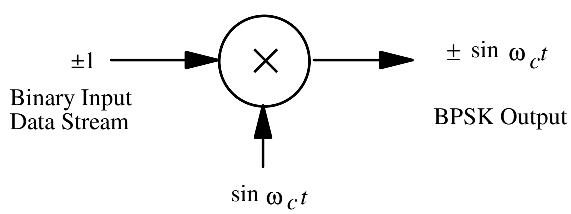



## 5.5 Phase Modulation

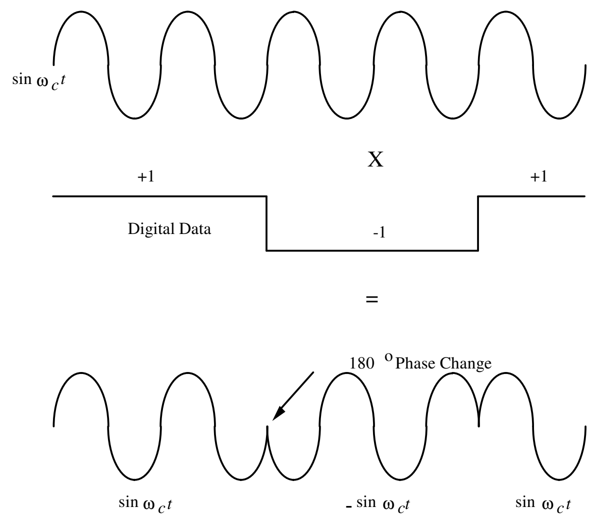
All high performance modems today use some form of phase modulation.

### 5.5.1 BPSK Modulator

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.

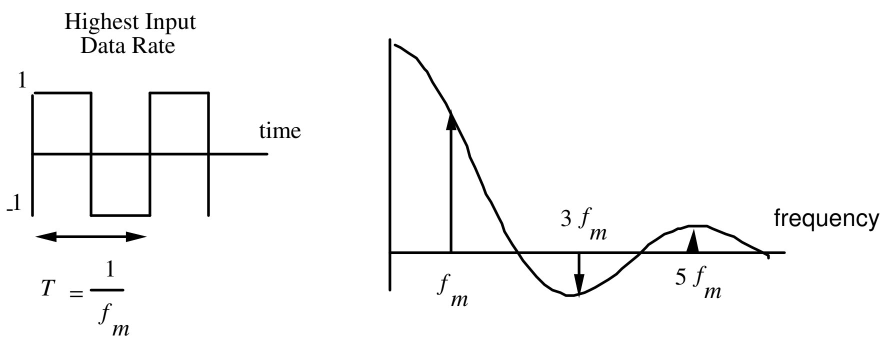


The output has two phase states:

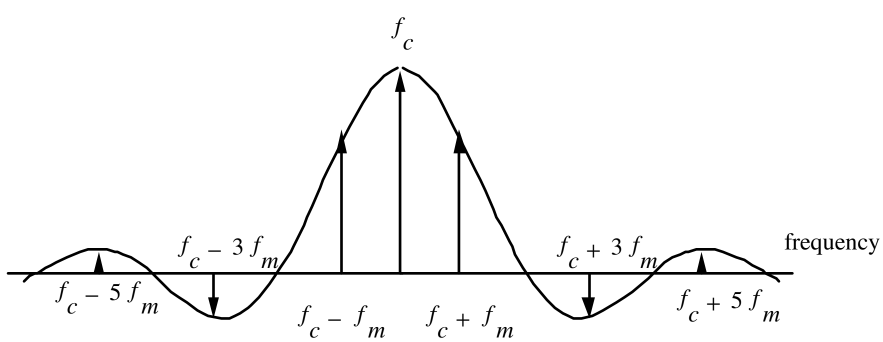



In the above illustration, the duration of each of the phase states corresponds to one signaling element or baud. The baud rate is therefor equal to the bit rate.

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.

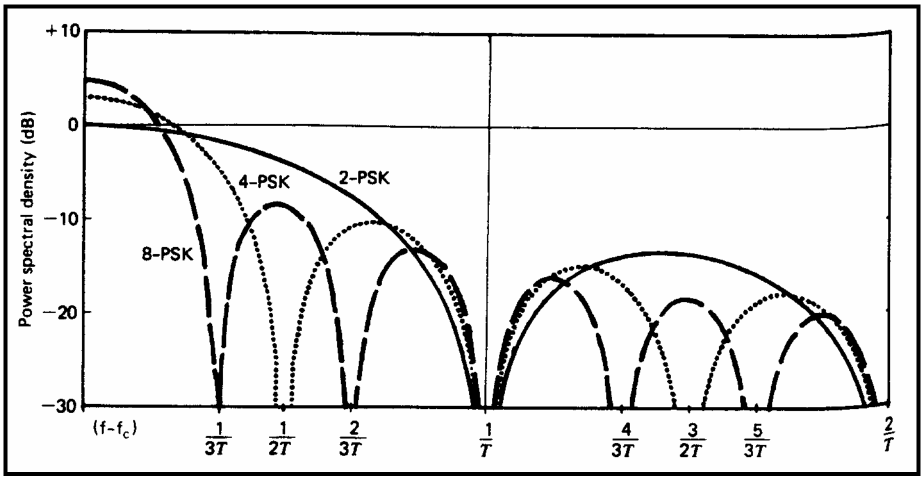



The resultant BPSK spectrum is:



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

PSK Spectra[1]




## 5.6 Vector (QPSK) Modulators

[QPSK System using Ideal Components by Elanix](#)

[QPSK System using Baseband Processing by Elanix](#)

[QPSK System using Real Components by Elanix](#)

http://www.educatorscorner.com/experiments/spectral/SpecAn10.shtml

Quadrature modulation uses two data channels denoted I[†] and Q[†] displaced by 90° 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.

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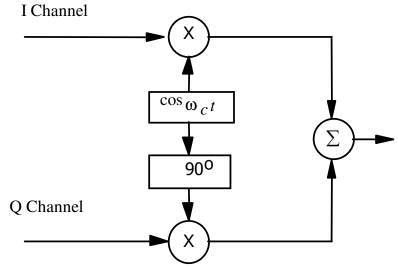
1 *Digital Telephony* (2nd ed.), John Bellamy, Figure 6.15

† In phase

† Quadrature phase

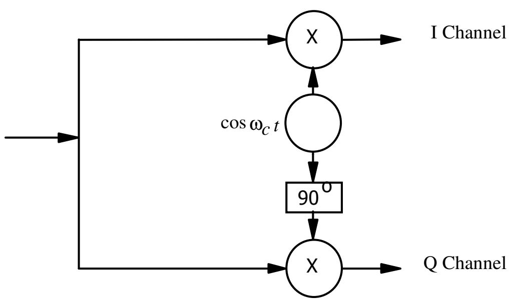
### Quadrature (or Vector) Modulator




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

### Quadrature Demodulator

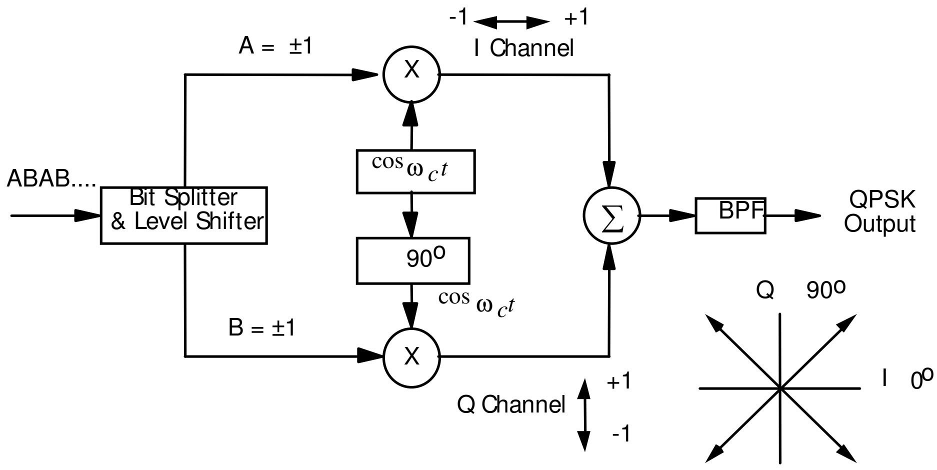
Quadrature Demodulator by Elanix



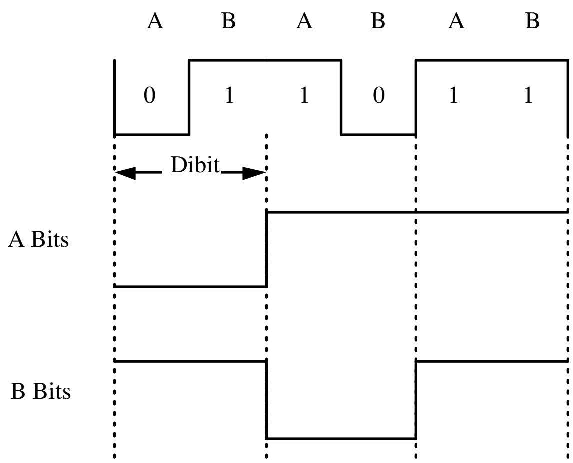

In the most basic configuration, there are 4 possible output phases. This suggests that each output symbol correspond to 2 bits of binary information. Since several bits can be encoded into a baud, the bit rate exceeds the baud rate.

## 5.6.1 201 Modem

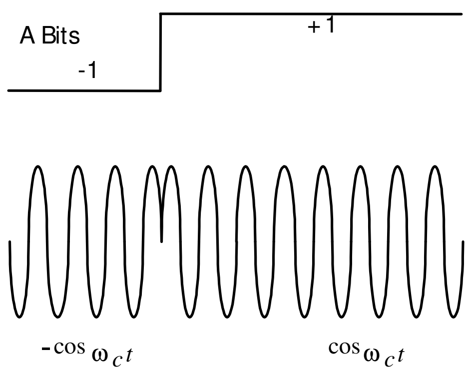
This modem has 4 output phase states each of which represents two bits of data.




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.

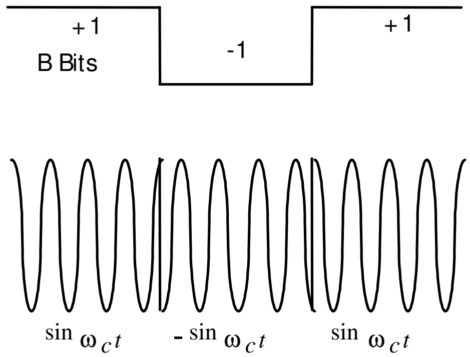



Each data stream is fed to a BPSK modulator. However, orthogonal carriers feed the two modulators. The output of the I channel modulator resembles:



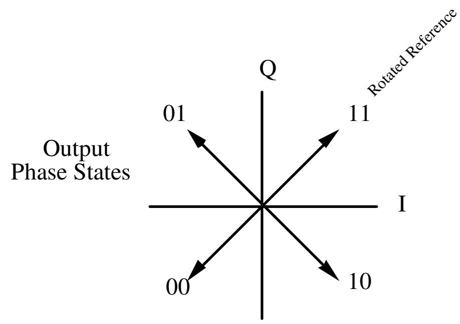

Output of I Channel Modulator

The output of the Q channel modulator resembles

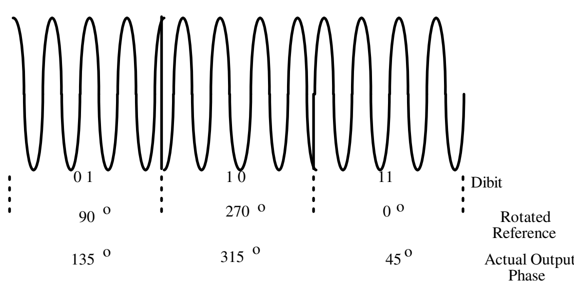



Output of Q Channel Modulator

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



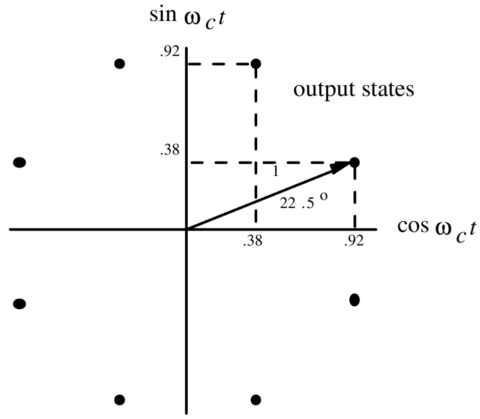

Rotating the output reference to 45° for the sake of clarity, the transmitted output for this particular data sequence is therefor:




### 5.6.2 8-PSK

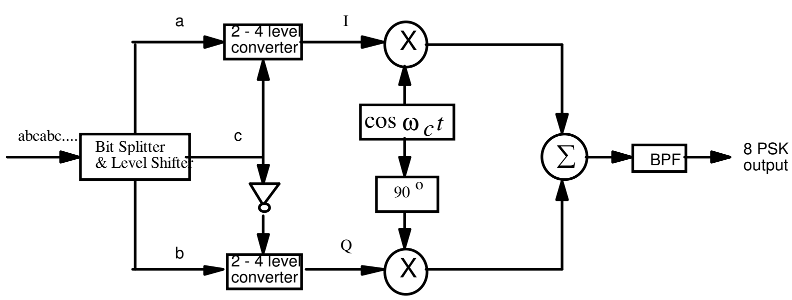
This process of encoding more bits into each output baud or phase state can be continued. Organizing binary bits into 3 bytes corresponds to 8 different conditions.

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.

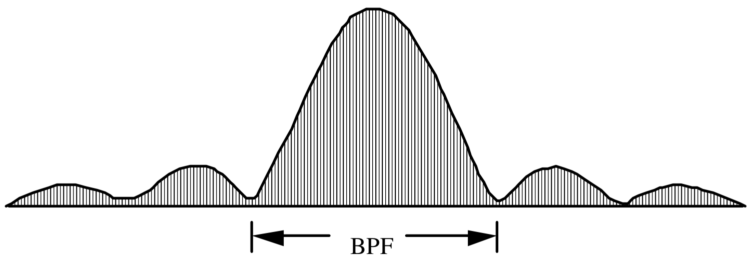
The input bit stream is organized into 3 bit bytes. Each bit is sent to a different location to control a certain aspect of the modulator. The inputs to the 2 - 4 level converter are 0's or 1's but the output is ± 0.38 or ± 0.92, depending on the C bit.



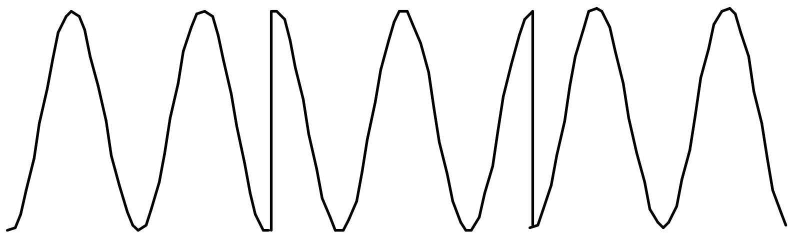

## 5.6.3 Continuous PSK

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.

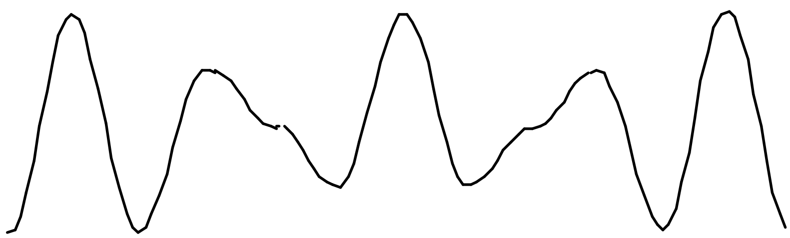
The unfiltered spectrum may resemble:



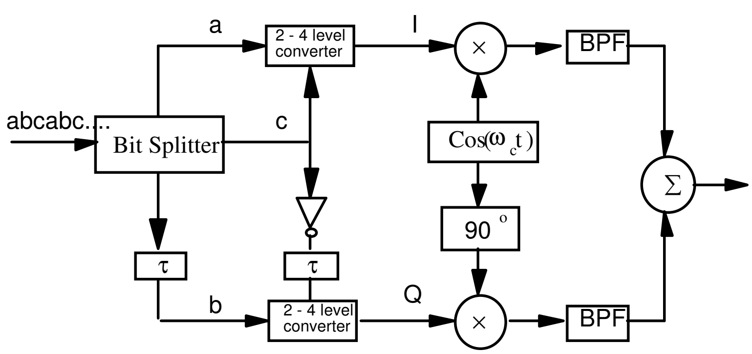

Before the bandpass filter, the phase-shifted signal may appear as:



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.



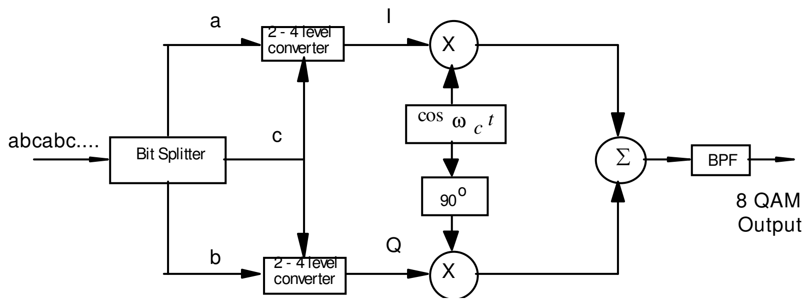

## 5.6.4 π/4 QPSK

## 5.6.5 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.

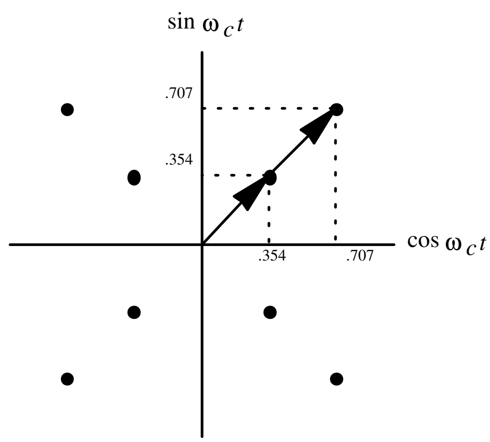
### 5.6.5.1 8-QAM

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.

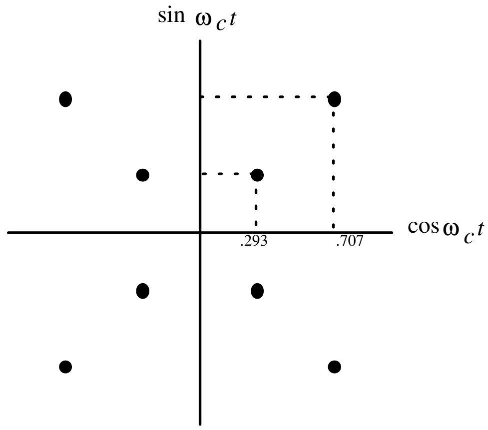



The a & b bits control the polarity in their respective channels, while the c bit governs the two possible amplitudes [Note: 0.5xSin(45°) = 0.354 and 1xSin(45°) = 0.707]

The constellation diagram for this system is:



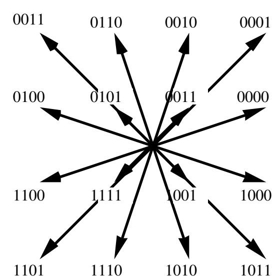

A slight improvement can be made to this example, by evenly spacing the data points [and therefor making all of the eye openings equal], as follows:

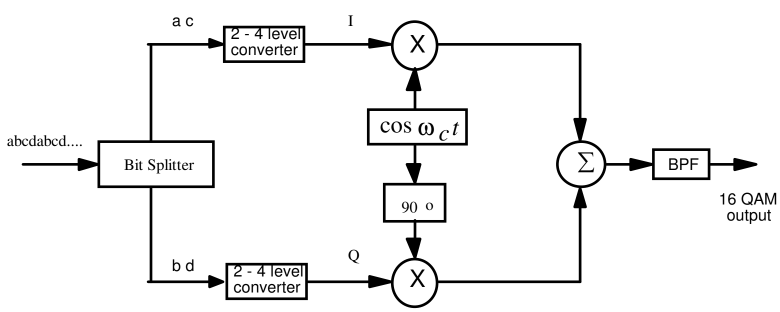



SystemView BY ELANIX

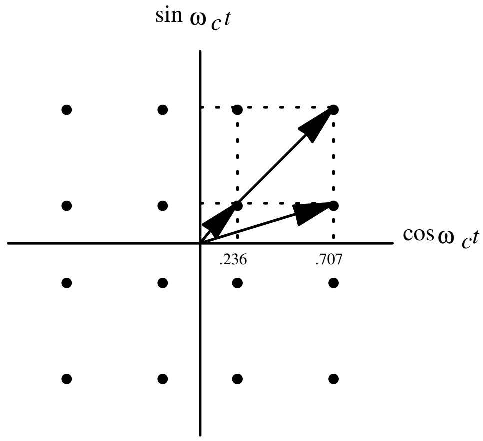
### 5.6.5.2 209 Modem 16-QAM

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.

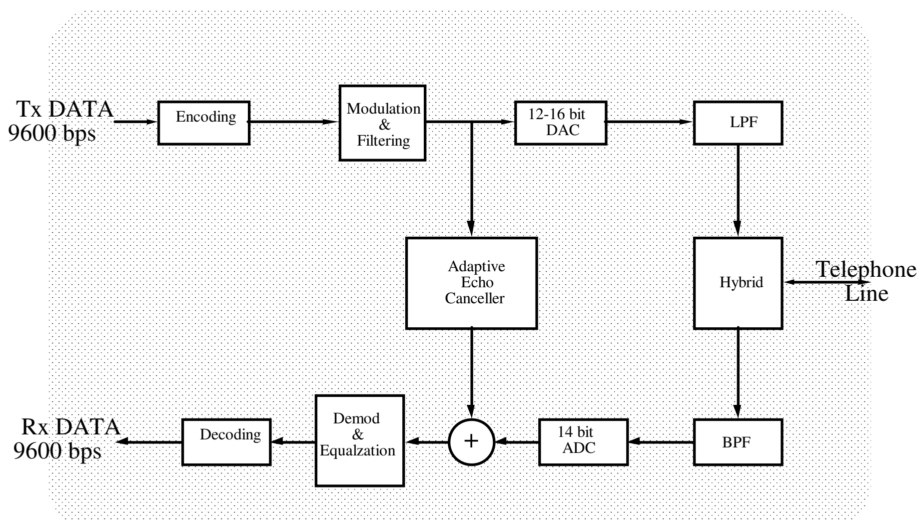



One possibility is to let the a and b bits control the polarity, and the c and d bits control the 2-4 level converter output amplitude. For the sake of comparisons, the maximum QAM output amplitude has again been fixed at 1.



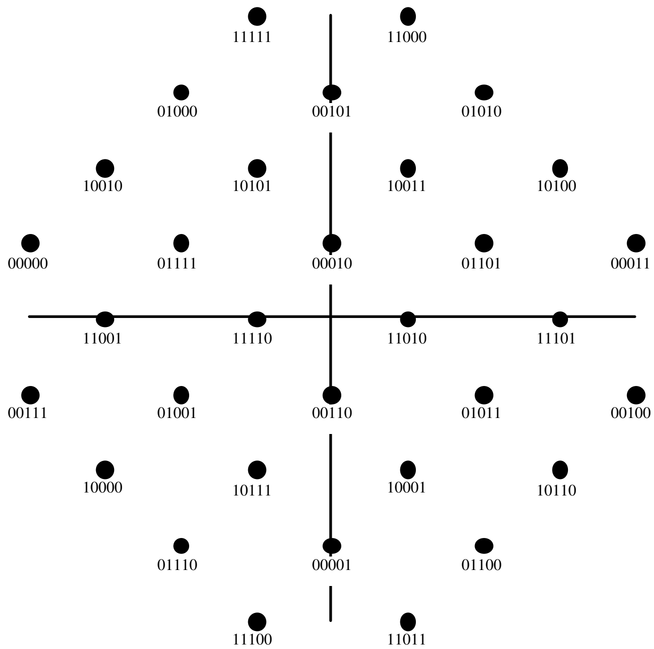

### 5.6.5.3 V.32 MODEM




The V.32 modem was once the premier device for communicating over voice grade lines. Its basic characteristics include:

- 9600 bps transmission rate
- 1800 Hz carrier frequency [transmit & receive]
- 2400 baud
- 4 data + 1 redundancy bits per symbol
- 32 QAM Trellis coded
- Utilizes echo cancellation

The output constellation diagram resembles:




### 5.6.5.4 56K MODEM

There are two principal manufacturing groups of 56 Kbps modems. One is lead by Rockwell and the other by 3Com [formerly USRobotics]. Unfortunately, these two devices are not compatible. The ITU is attempting to create a standard, and once it emerges, the existing products will be upgradeable. The Open56K forum will provide interoperability and backward compatibility among 56K modems. Some alliance members include Motorola, Rockwell, Ascend, Epoch and Lucent.

The 56K modem has been adopted by more than 100 modem manufacturers and 300 Internet providers worldwide.

This technique relies on there be only 1 digital to analog conversion, that being at the end-users line. The rest of the link must be digital. This is possible since most internet service providers use all digital links to the PSTN. However, the ISP side must employ the same technology, otherwise the connection will fall back to the V.34 rate.

### 5.6.5.5 Rockwell K56

Rockwell has produced more than 100 million modem chipsets of various kinds. These are found in 75% of the world's personal computer modems.

Users can download at up to 56 Kbps while the upload speed is limited to 33.6 Kbps over an analog loop. The 56 Kbps limitation is due to the *a* and *b* bit signaling scheme used on DS-1 links.

Some 56K variants also support V.80 video conferencing and full duplex speakerphone.

56K modems automatically connect at the highest rate the network and line conditions allow by falling back in 2 K increments between 56 K and 33.6 Kbps. They are also backward compatible with 33.6, 28.8, 14.4 Kbps and slower modems.

K56 supports V.42 and MNP 2-4 error control and the T.30 fax standard, is auto configurable or plug-n-play, and new features can be added as software upgrades.

### 5.6.5.6 3Com 56K

Quantization noise limits the communications channel to about 35K however, it only affects the analog-to-digital conversion. If there are no analog-to-digital conversions between the x2 server modem and the PSTN, and it uses only the 255 signal levels, then the exact digital information reaches the client modem's receiver, and no information is lost in conversion.

Even under the best conditions, when a signal undergoes analog-to-digital conversion, there is a 38 to 39 dB signal-to-noise ratio. This limits practical V.34 speeds to 33.6 Kbps.

The server connects, digitally to the telco. The server signaling is such that the encoding process uses only the 256 PCM codes used in the digital portion of the telephone network. Since there is no intermediate analog processing, there is no quantization noise.

The end-user's downstream modem channel is capable of higher speeds because no information is lost in the digital-to-analog conversion. Since the upstream channel goes through an analog-to-digital conversion, the transmission rate is limited to V.34 speeds.

Data is sent digitally from the server modem over the PSTN, and its symbol rate must equal the PSTN sample rate.

During the training sequence, x2 modems probe the line to determine whether any downstream analog-to-digital conversions have taken place. If any are detected, they connect in the V.34 mode.

Ideally, the end-user modem should resolve all 256 codec levels and thus support 64Kbps. However, this is not possible since noise arises from various nonlinear distortions and circuit crosstalk.

The greatest source of non-linearity is the voice codec in the BORSCHT circuit on the subscriber loop. It follows the μ-law companding scheme. It is impractical to use all 256 discrete codes, because the DAC voltage levels near zero are too close to be resolved.

Therefore, the x2 encoder uses various subsets of the 256 codes that eliminate DAC output signals most susceptible to noise. The most robust 128 levels are used for 56 Kbps. Using fewer levels provides more robust operation, but at a lower data rate.

One end of an x2 connection must terminate at a digital circuit, such as a T1, ISDN PRI, or ISDN BRI.

## 5.7 OFDM

Orthogonal frequency division multiplexing.

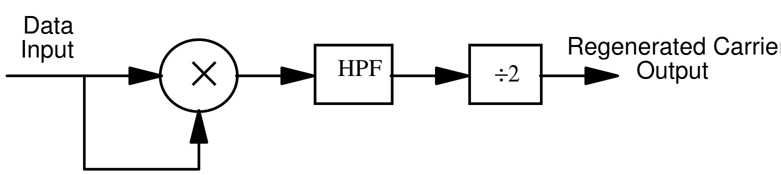
Multi-Carrier Modulation by Linnartz
W-OFM Modulation by WiLAN
Technical Details of WODM by WiLAN

http://www.ofdm-forum.com/content/page1.html
http://www.wi-lan.com/ofdm/first.html
http://spacecom.grc.nasa.gov/technologies/digital/odfm.asp
http://pcsrv1.comm.uni-bremen.de/pub/mcarrier/index.html


## 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




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: $\frac{1}{2}\cos(2\omega_i t \pm \pi)$

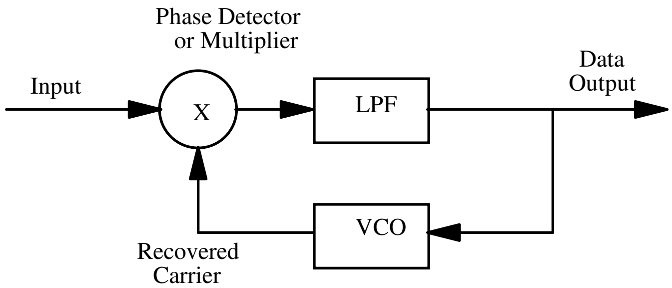
The sign inversion in front of $\pi$ is of no consequence since cosine is an even function.

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.




let the input = $\sin(\omega_i t)$

let the VCO output = $\cos(\omega_0 t + \theta)$

Then the multiplier output is:

$$\sin(\omega_i t)\cos(\omega_0 t + \theta) = \frac{1}{2}\sin(\omega_i t + \omega_0 t + \theta) + \frac{1}{2}\sin(\omega_i t - \omega_0 t - \theta)$$

After the LPF we obtain:

$$\frac{1}{2}\sin(\omega_i t - \omega_0 t - \theta)$$

If $\omega_i \neq \omega_0$ then $\theta$ is irrelevant and the circuit is not in lock.

However, if

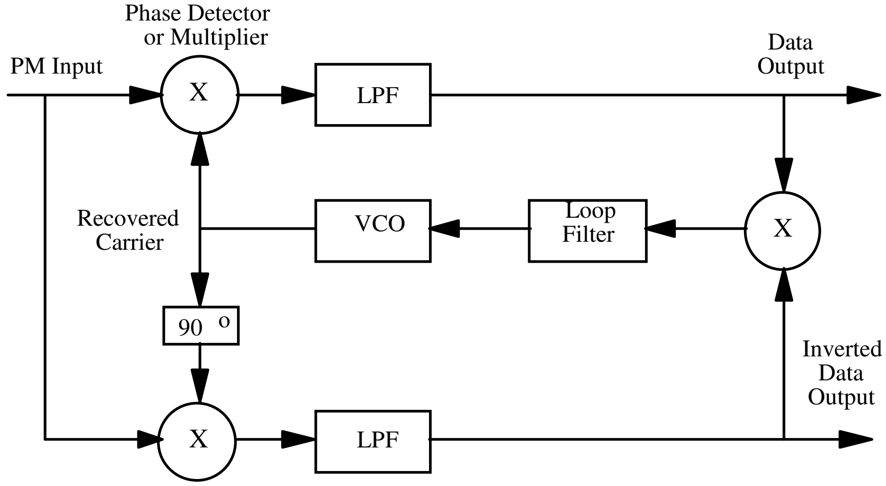
$\omega_i \succ \omega_0$ the output is positive

$\omega_i \prec \omega_0$ the output is negative

Therefore this signal can be used to drive the VCO in such a way that it will force $\omega_i = \omega_0$. This is the frequency locked state.

When $\omega_i = \omega_0$, then the output of the LPF is $\frac{1}{2}\sin(-\theta)$, where $\theta$ 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:

| | |
|---|---|
| Input | $= \pm\sin(\omega_i t)$ |
| VCO Output | $= \cos(\omega_o t)$ |
| Top Multiplier Output | $= \frac{1}{2}\sin(\omega_i t + \omega_o t) + \frac{1}{2}\sin(\omega_i t - \omega_o t)$ |
| After the LPF | $= \frac{1}{2}\sin(\omega_i t - \omega_o t)$ |
| Bottom Multiplier Output | $= -\frac{1}{2}\cos(\omega_i t + \omega_o t) + \frac{1}{2}\cos(\omega_i t - \omega_o t)$ |
| After the LPF | $= \frac{1}{2}\cos(\omega_i t - \omega_o t)$ |

The output of the right hand multiplier will then be:

$$\frac{1}{2}\sin(\omega_i t - \omega_o t)\frac{1}{2}\cos(\omega_i t - \omega_o t) = \frac{1}{4}\sin(2(\omega_i - \omega_o)t)$$

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 $\omega_i = \omega_0$, then:

$$\text{Input} = \pm\sin(\omega_i t)$$

$$\text{VCO Output} = \cos(\omega_i t + \theta)$$

$$\text{Top Multiplier Output} = \frac{1}{2}\sin(\omega_i t + \omega_i t + \theta) + \frac{1}{2}\sin(\omega_i t - \omega_i t - \theta)$$

$$\text{After the LPF} = \frac{1}{2}\sin(-\theta)$$

$$\text{Bottom Multiplier Output} = \frac{1}{2}\cos(\omega_i t + \omega_i t + \theta) + \frac{1}{2}\cos(\omega_i t - \omega_i t - \theta)$$

$$\text{After the LPF} = \frac{1}{2}\cos(-\theta)$$

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

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

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

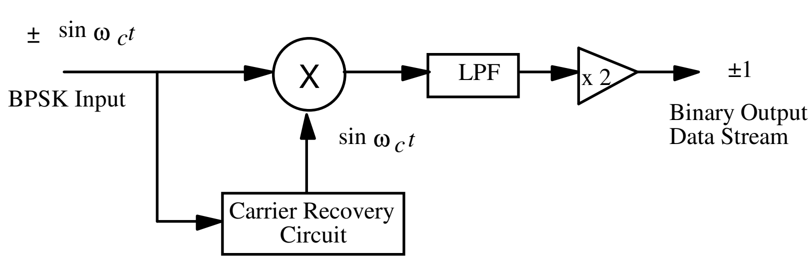
Note however that this function is now cyclic and the Costas loop may lock into 1 of 2 possible states. Consequently, data may appear in either output. For this reason, differential encoding of the data must be employed.

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.



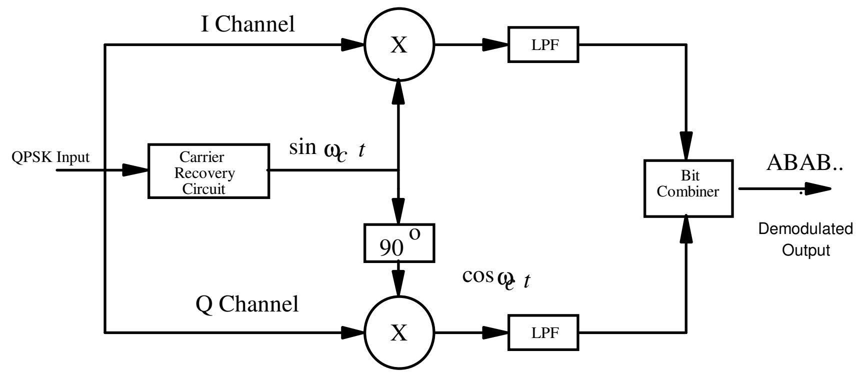

The signal appearing out of the multiplier is:

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

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:

$$[\pm\sin(\omega_c t)\pm\cos(\omega_c t)]\sin(\omega_c t)$$

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

$$=\pm\left[\frac{1}{2}-\frac{1}{2}\cos(2\omega_c t)\right]\pm\left[\frac{1}{2}\sin(2\omega_c t)+0\right]$$

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:

$$[\pm\sin(\omega_c t)\pm\cos(\omega_c t)]\cos(\omega_c t)$$
$$=\pm\left[\frac{1}{2}\sin(\omega_c t-\omega_c t)-\frac{1}{2}\sin(\omega_c t+\omega_c t)\right]\pm\left[\frac{1}{2}\cos(\omega_c t-\omega_c t)+\frac{1}{2}\cos(\omega_c t+\omega_c t)\right]$$
$$=\pm\left[\frac{1}{2}\sin(2\omega_c t)-0\right]\pm\left[\frac{1}{2}+\frac{1}{2}\cos(2\omega_c t)\right]$$

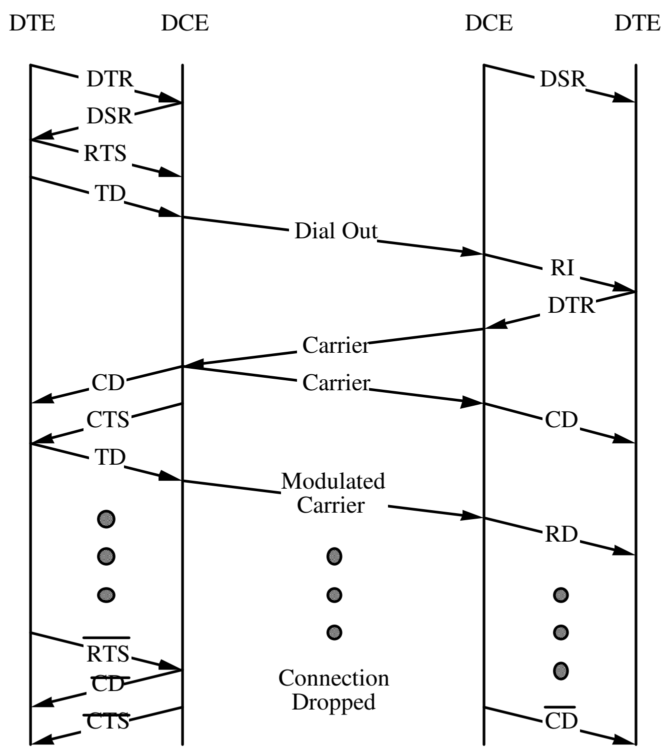
After the LPF, we obtain: $\pm\frac{1}{2}$ Note that this bit value occurs because of the product:

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

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

## 5.5 Dial-up Operation

In the idle mode, the modem will set the DCE pin high while the terminal sets the DTE pin high. This indicates that each device is ready to respond to the needs of the other. A generic dial-up process is illustrated as follows:




The secondary or reverse channel allows the modem to operate in the full duplex mode. It is often used to verify the data path integrity. If the secondary carrier disappears, it indicates that the far end modem is no longer receiving properly.

### 5.5.1 Communications Software

The purpose of this type of software is to make it easier to use a modem. It can operate in two modes: command mode, and terminal mode. The interaction in the command mode is strictly local. In the terminal mode, the interaction is with the far end.

In order to request and retrieve a file, both modes are needed. In the terminal mode, the number is dialed, access achieved, and a request for information sent. Once this is done, it is necessary to switch to the command mode and inform the local computer to receive and store the incoming data.

The software must also regulate the flow of information to prevent the receiving station from being swamped. This is accomplished by using XON and XOFF codes.

Many PCs have fax modems. When the modem detects a ringing line, it sets the RI indicator and the computer invokes its communications software. The modem picks up the line, detects an incoming carrier and sets its DCD indicator; the PC performs some handshaking and receives the fax.

Binary data from the DTE may be organized in two basic ways: asynchronously or synchronously. It should be noted that the signal transmitted by the DCE to the loop might be synchronous even if the data format is not.

Asynchronous Data

- Usually used on low speed terminals [< 2 Kbps]
- Start and stop bits bracket each character
- The codes used are of variable length: Baudot = 5 bits; ASCII = 7 bits; EBCDIC = 8 bits

Synchronous Data

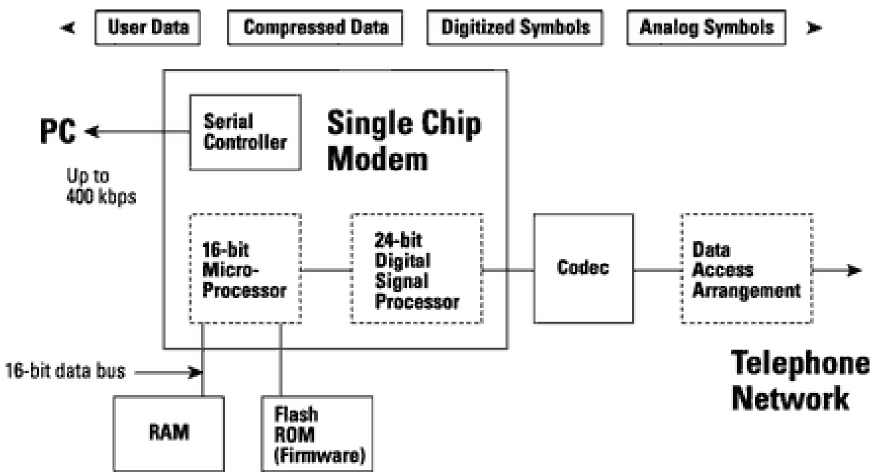
- Data is transferred in blocks without interruption
- A scrambler is often used to prevent long strings of 1s or 0s causing loss of lock

### 5.5.2 Protocols

- BOP - Bit Oriented Protocol
- SLDC - Synchronous Data Link Control - developed by IBM
- BCP - Byte Controlled Protocol
- BSC - Binary Synchronous Communications Protocol

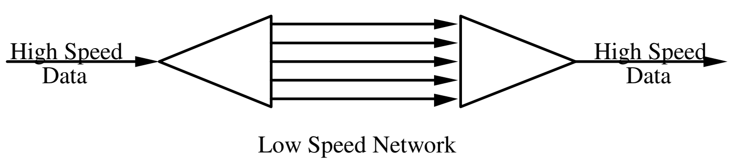
## 5.6 Internal PC Modems

Many personal computers are coming equipped with an internal modem. These operate slightly different from the standard external modem, since they do not require an RS-232 interface. In some cases, these modems are also fax machines.




## 5.7 Inverse Multiplexing

Inverse multiplexers allow data customers transmit high information rates through low bandwidth telephone loops.




The originating end establishes a connection through a dial-up modem. The terminating end then sends back a list of local telephone numbers of other available lines. The originating unit then dials up additional lines needed to carry the required bit rate.

Since each of these connections may take a different path through the telephone network, the delays on each channel must be determined. The originating unit then breaks down the high-speed data into a number of low speed streams and places them on the individual circuits. The receiving unit must recombine the multiple low channels, taking delay into account, in order to recreate the original data stream.

Notes

## 5.8 Modem Standards

A standard is a technology agreed upon by the various vendors in an industry and ratified by an international governing body. New standards are driven by market trends, technological advancements, and consumer demand. Standards in the modem industry begin as proprietary technologies submitted by individual vendors to the International Telecommunications Union (ITU), the formal worldwide telecommunications standards body whose charter organization is the United Nations. The ITU may adopt a proprietary protocol from an individual vendor. Or they may adopt a standard based on technologies from different vendors.

Standards are initially "determined," then later ratified or "decided." A determined standard is based on a technical agreement between active union participants. Once determined, the core technology of a standard won't change. Moreover, vendors develop and ship product based on determined standards. Determined standards are later agreed upon by all members of the UN and considered ratified.

### Bell Standard Modems

| Modem | Modulation | bps | Comments |
|---|---|---|---|
| 103 | FSK | 300 | |
| 113 | FSK | 300 | Originate or Answer |
| 201 | 4 PM | 2400 | |
| 202 | FSK | 1200, 1800 | |
| 208 | 8 PM | 4800 | Auto answer |
| 209 | QAM | 9600 | Requires D1 line conditioning |
| 212 | PM | 300, 1200 | Auto answer |

In more recent times, a UN founded organization, the ITU [formerly the CCITT], has created standards that have a greater international appeal.

## CCITT Modem Summary

| Modem | Modulation | bps | Baud | Comments |
|---|---|---|---|---|
| V.17 | QAM | 7200-14400 | 7400 | |
| V.21 | FSK | 300 | 300 | Full Duplex - Bell 103 |
| V.21bis | QAM | 2400 | 600 | Full Duplex |
| V.22 | 4 - DPSK | 1200 | 600 | Full Duplex |
| V.22bis | QAM | 2400 | 600 | Full Duplex - Bell 212A |
| V.23 | FM | 1200/75 | 2100/1300 & 450/390 | 75 bps reverse channel |
| V.26 | 4 - DPSK | 2400 | 1200 | Full Duplex |
| V.26bis | PSK | 2400 | 1200 | Half Duplex |
| V.26terbo | PSK | 2400/120 | 1200 | full duplex |
| V.27 | PSK | 4800 | 1600 | |
| V.27bis | PSK | 1600/1200 | | |
| V.27terbo | PSK | 4800/2400 | 1600/12 | Group 3 fax |
| V.29 | PSK/QAM | 9600/7200/ 4800 | 2400 | Group 3 fax |
| V.32 | QAM | 9600/48 | 2400 | Full Duplex |
| V.32bis | TCQAM | 4800-14400 | 2400 | |
| V.32terbo | TCQAM | 14400- 19200 | 2400 | |
| V.32fast | TCQAM | to 28800 | to 3429 | |
| V.33 | TCQAM | 14400 | 2400 | |
| V.36 | | 48000 | | Group line modem |
| V.37 | | 72000 | | Group line modem |

ITU-T The International Telecommunications Union Telecommunication Standardization Sector (formerly called the CCITT) makes recommendations for global telecommunications standards.

## ITU V Standards[2]

- V.1 Defines bits as mark/space voltage levels
- V.2 Modems line levels
- V.4 The data frame
- V.5 Synchronous signaling rates for dial-up lines
- V.6 Synchronous signaling rates on leased lines
- V.7 A list of modem terms in English, French, and Spanish
- V.10 Unbalanced high speed interfaces [RS-423]
- V.11 Balanced high speed interfaces [RS-422]
- V.14 Asynchronous to synchronous conversion
- V.15 Telephone acoustic couplers
- V.17 Group 3 fax modulation. Two wire, half-duplex, trellis coded, 7200, 9600, 12000, & 14400 bps.
- V.18 Interoperability for communications devices for the deaf.

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

V.19 DTMF modems

V.21 300 bps FSK modem [Bell 103]

V.22 1200 bps [600 baud] FSK modem [Bell 112A]

V.22bis QAM 2400 bps modems

V.23 FM 1200/75 bps modem used on some videotext systems. The 75 bps rate is the reverse channel rate.

V.24 Connection between DCE and DTE. Effectively the same as RS232, though it only specifies the meaning of the signals, not the connector or voltages.

V.25 Automatic answering equipment

V.25bis A cryptic command language for modems. Defines serial automatic calling and answering and is equivalent to the Hayes AT commands

V.26 2400 bps [1200 baud] full duplex PSK modem

V.26bis 2400 bps [1200 baud] half duplex PSK modem

V.26terbo 2400/1200 bps [1200 baud] PSK full duplex modem

V.27 4800 bps [1600 baud] PSK modem

V.27bis 4800/2400 [1600/1200 baud] PSK modem

V.27terbo 4800/2400 PSK modem, used for half duplex Group 3 fax at 1600/1200 baud

V.28 Defines the electrical characteristics of V.24 or RS-232

V.29 9600/7200/4800/ [2400 baud] PSK/QAM modem. Often used for Group 3 fax

V.32 9600/4800 [2400 baud] QAM full duplex modem using trellis coding and echo cancellation

V.32bis 4800/7200/9600/12000/14400 [2400 baud] TCQAM full duplex modem using trellis coding, echo cancellation, and automatic rate adaptation. This is a very popular modem for PCs.

V.32terbo 14400/16800/19200 [2400 baud] TCQAM full duplex modem using trellis coding, echo cancellation, and automatic rate adaptation.

V.32fast The informal name for an unfinished standard that may be renamed V.34 when ratified. It may replace the V.32bis with speeds up to 28800 bps; it may also be the last analog protocol.

V.33 14400 bps [2400 baud] TCQAM full duplex modem

V.34 The ratified version of V.32fast. 28800bps It is expected to provide speeds up to 128 Kbps [3429 baud]

V.36 Specialized multi line 48000 bps group modem

V.42 Defines the two stage detection and negotiation of LAPM error control Error correction with asynchronous to synchronous conversion. Includes MNP-1 through MNP-4 and LAP M. Not used by UUCP, kermit, xmodem, etc., since they do their own error correction.

V.42bis Extends V.42 to include data compression

V.50 Sets standard telephony limits for modern transmission quality

V.51 Maintenance requirements of international circuits

V.52 Measurement of data distortion and error rates

V.53 Impairment limits for data circuits

V.54 Loop testing devices. Modem diagnostics standard frequently included by V.32 modems.

V.55 Impulse noise measurement

V.56 Comparative modem testing procedures

V.57 High speed data transmission test equipment

V.100 Interconnection techniques between PDNs and PSTNs

Proprietary Protocols

HST - 9600bps/14.4kbps/16.8kbps/21kbps/24kbps "High Speed Technology", US Robotics' proprietary full duplex protocol. USR puts out modems that use HST, modems that use V.32bis, and modems that support both standards, called "dual-standard".

PEP - "Packetized Ensemble Protocol", Telebit's proprietary 9600bps full duplex error-correcting protocol. Reported to sustain noisy connections better than V.32. TurboPEP is an improvement, and can achieve 24000bps or more.

Express 96 - "Ping Pong Protocol", Hayes' proprietary 9600bps protocol.

CSP - "CompuCom Speed Protocol", CompuCom's proprietary 9600bps protocol. In 1992, the SpeedModem Champ was unique in that it was cheaper than V.32, but CompuCom went out of business.

MNP - "Microcom Network Protocols"

MNP1 Asynchronous, half duplex transfer.

MNP2 Simple error correction, asynchronous, full duplex.

MNP3 Error correction, synchronous. Not a big win over MNP2.

MNP4 Error correction, better throughput than MNP2-3.

MNP5 Simple data compression, about 2:1. Often included with V.42.

MNP6 Statistical duplexing and Universal Link Negotiation. With V.29, modems can emulate full duplex operation. Also supports fall-forward operation between two MNP modems.

MNP7 Data compression, about 3:1.

MNP8 MNP7 for pseudo-duplex modems.

MNP9 Data compression, about 3:1. Includes V.32 technology. (?)

MNP10 Dynamic fall-back and fall-forward adjusts modulation speed with link quality.

LAPM "Link Access Protocol for Modems". AT&T/Hayes error correction standard. Included in V.42.

CAS IBM and DCA standard for computer-fax modem interface.

Class 1 Electronic Industries Association/Telecommunications Industry Association standard for minimal computer-fax modem interface.

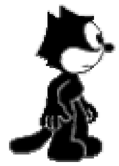
Class 2 EIA/TIA standard for extended computer-fax modem interface.

_____ Notes _____

Group 3 Fax protocol.  9600bps.  203x98dpi/203x196dpi.  Compression.

Group 4 Fax protocol.

# Review Questions



## Quick Quiz

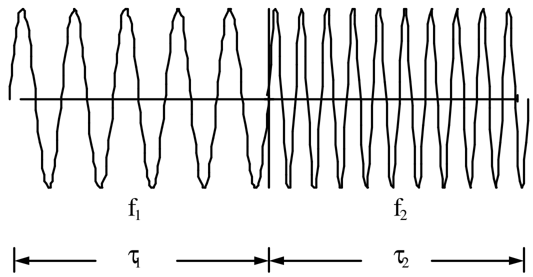
1. The [DTE, DCE] is the source of information.
2. A simplex connection takes [a greater, the same, a lesser] number of wires than a half-duplex connection.
3. Most modems transmit [asynchronous, synchronous] data.
4. Null modems do not require a power source. [True, False]
5. The simplest modulation 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.

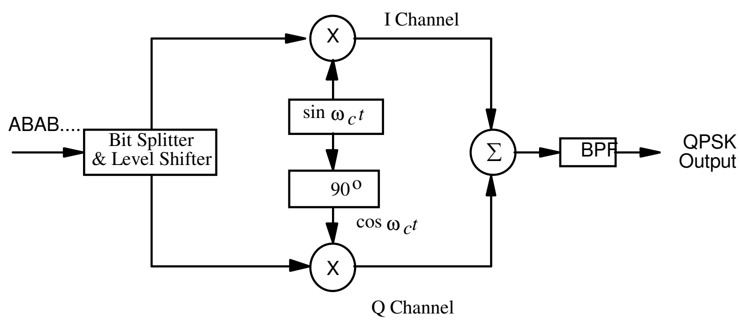
2. Sketch the approximate spectrum of an FSK signal where:

   - $f_1 = 1000$ 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.

## SystemView Models

1. Make a model of a 1 Kbps BPSK modulator.
2. Make a model of a 1 Kbps BFSK modulator.
3. Make a model of a 64 Kbps 16 QAM modulator.

# For Further Research

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