CSE / T / 315A
Data Communications
Topic 5- Analog Transmission

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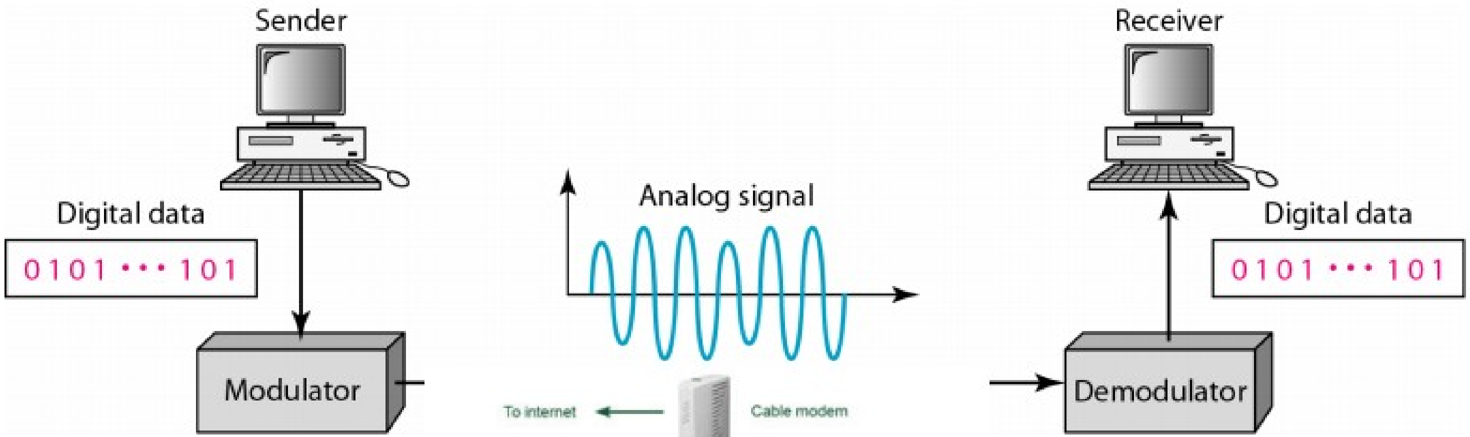
Overview

- Digital-to-analog conversion is the process of changing one of the characteristics of an analog signal based on the information in digital data.
- Analog- to-analog conversion is the representation of analog information be an analog signal. Modulation needed if the medium is bandpass in nature.

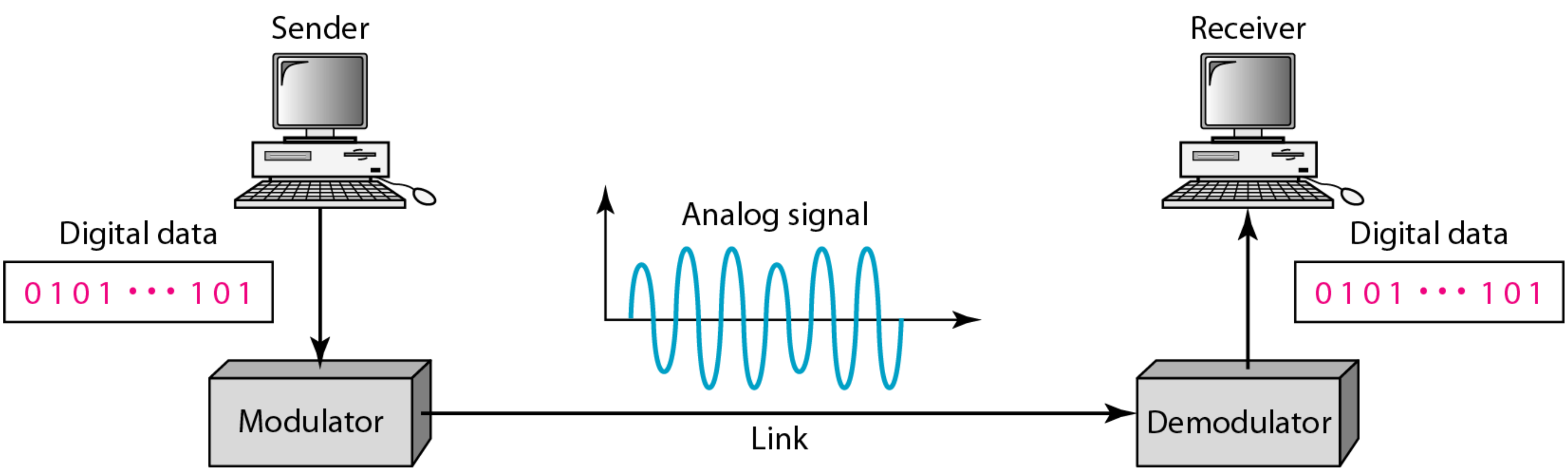
Why do we need digital to analog conversion?



The medium/channel is band pass

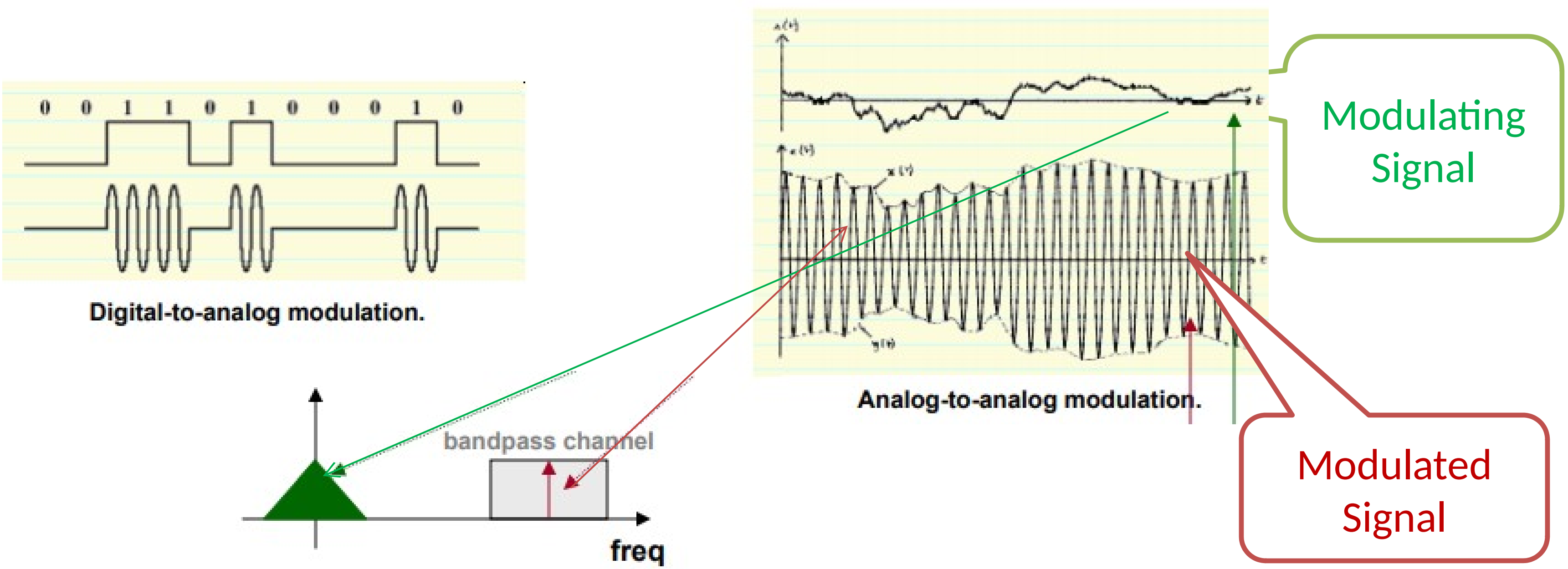
Digital to Analog Conversion

- Digital data needs to be carried on an analog signal.
- A carrier signal (frequency f_c) performs the function of transporting the digital data in an analog waveform.
- The analog carrier signal is manipulated to uniquely identify the digital data being carried.



Modulation of digital data

- Modulation: process of converting digital data or a low-pass analog to band-pass (higher-frequency) analog signal.
- Carrier Signal: aka carrier frequency or modulated signal - high frequency signal that acts as a basis for the information signal.
- Information signal is called modulating signal.



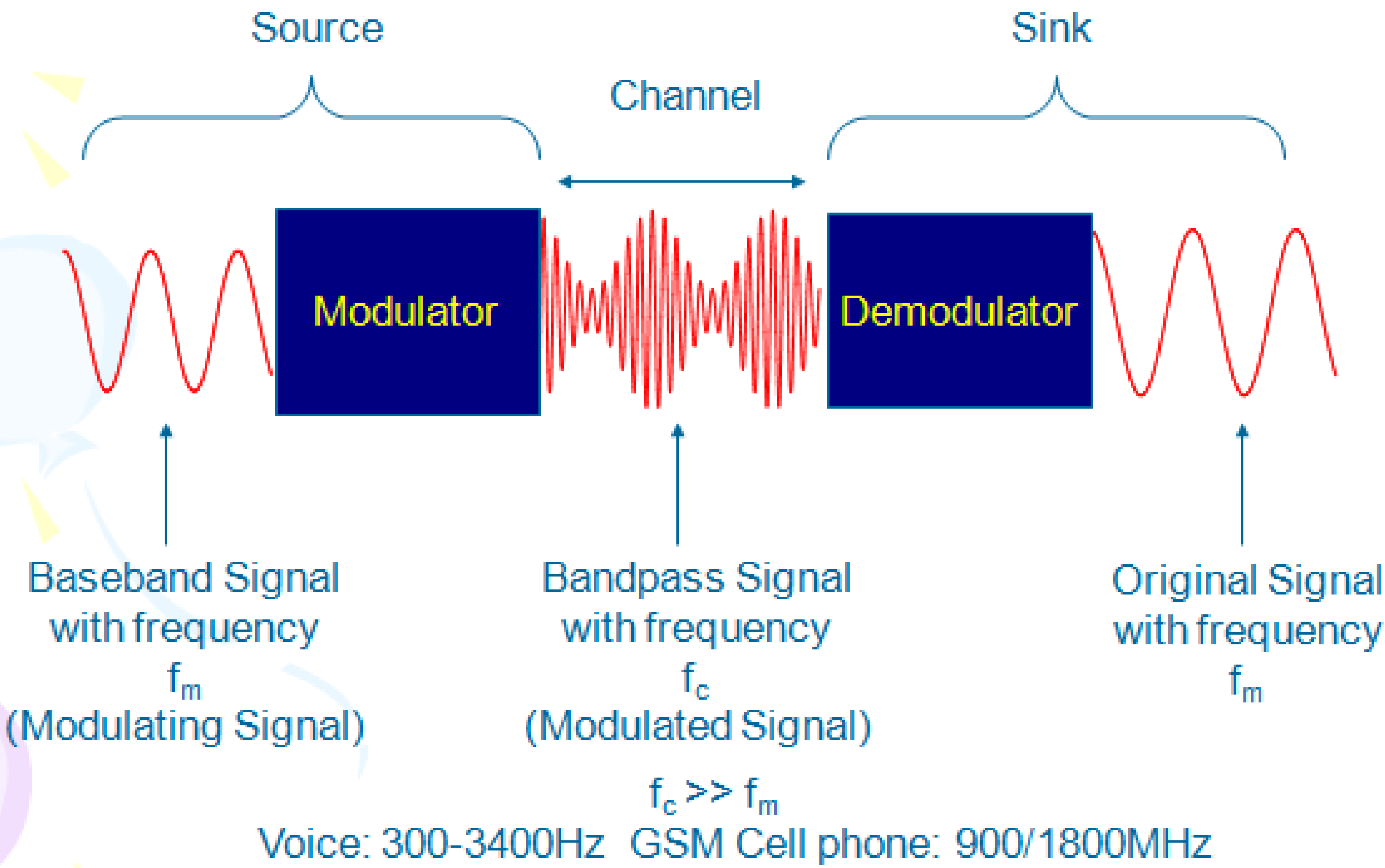
Modulation

- Modulation
  - In the modulation process, some characteristic of a high-frequency carrier signal (bandpass), is changed according to the instantaneous amplitude of the information (baseband) signal.
- Why Modulation
  - Suitable for signal transmission (distance…etc)
  - Multiple signals transmitted on the same channel
  - Capacitive or inductive devices require high frequency AC input (carrier) to operate.
  - Stability and noise rejection
- Application Examples
  - broadcasting of both audio and video signals
  - Mobile radio communications, such as cell phone

Digital to Analog Modulation

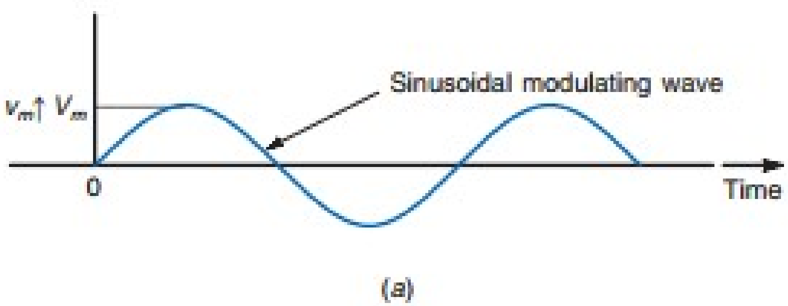
- Process of changing one of the characteristic of an analog signal (typically a sinewave) based on the information in a digital signal
- Sinewave is defined by 3 characteristics (amplitude, frequency, and phase) ⇒ digital data (binary 0 & 1) can be represented by varying any of the three
- Application: transmission of digital data over telephone wire (modem)

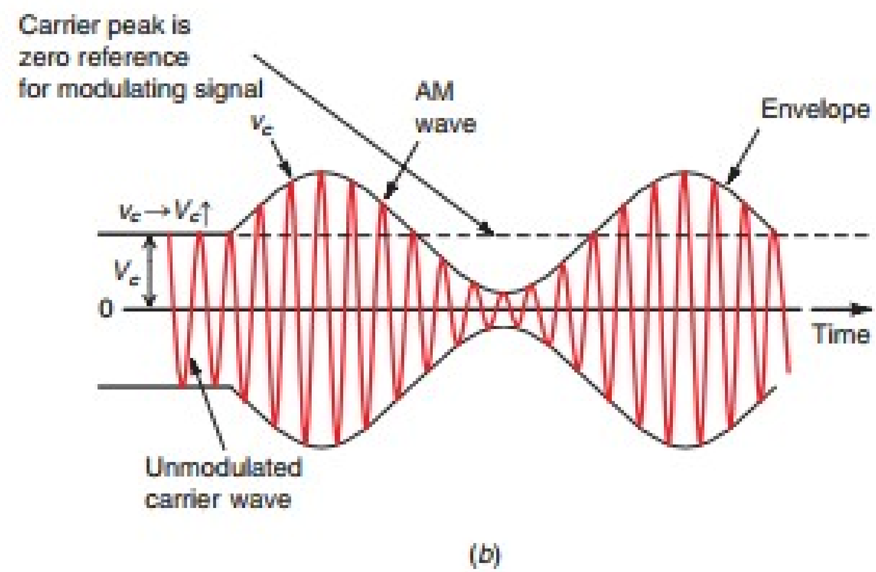
Modulation and Demodulation



Amplitude Modulation (AM) Concepts

- The information signal varies the amplitude of the carrier sine wave.
  - The instantaneous value of the carrier amplitude changes in accordance with the amplitude and frequency variations of the modulating signal.
  - Figure below shows a single frequency sine wave signal modulating a higher-frequency carrier.

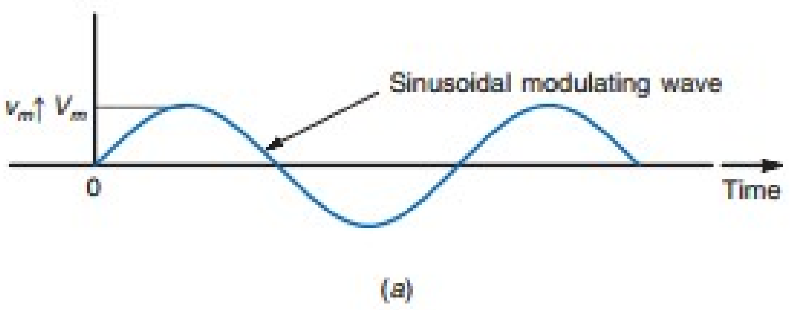




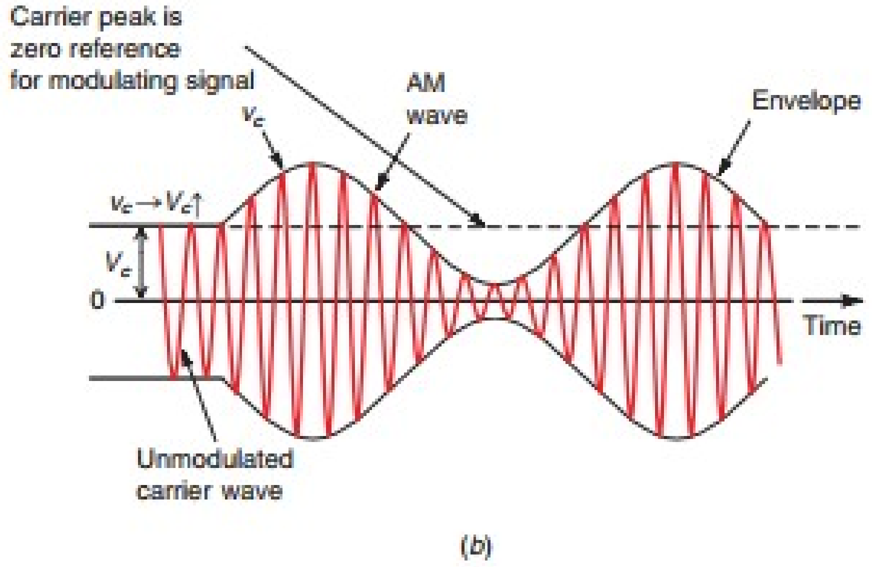
(a) The modulating or information signal (b) The modulated carrier

Amplitude Modulation (AM) Concepts

- The carrier frequency remains constant during the modulation process, but its amplitude varies in accordance with the modulating signal. An increase in the amplitude of the modulating signal causes the amplitude of the carrier to increase. Both the positive and the negative peaks of the carrier wave vary with the modulating signal. An increase or a decrease in the amplitude of the modulating signal causes a corresponding increase or decrease in both the positive and the negative peaks of the carrier amplitude.



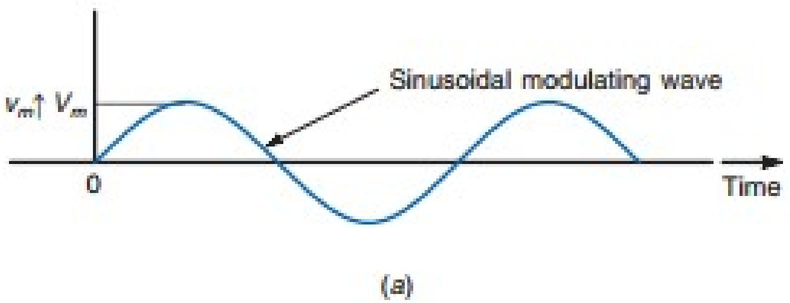
(a) The modulating or information signal

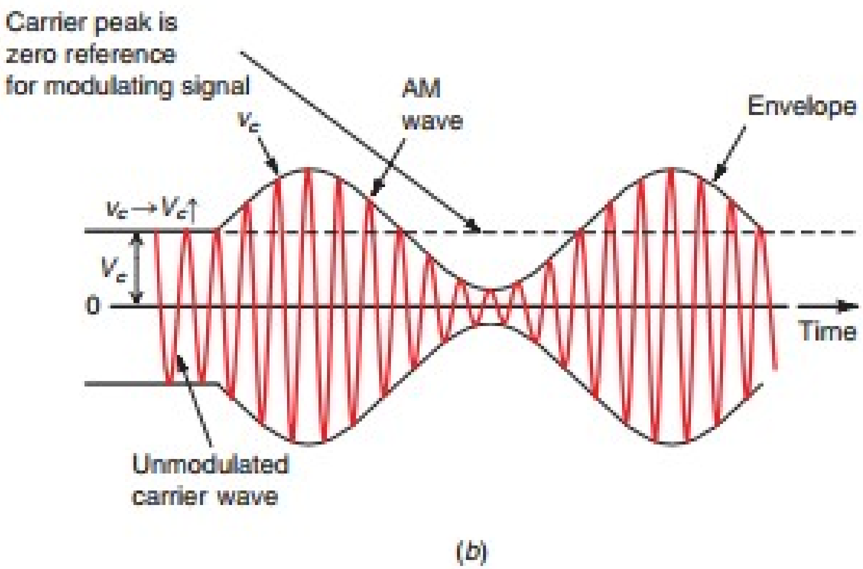


(b) The modulated carrier

Amplitude Modulation (AM) Concepts

- An imaginary line connecting the positive peaks and negative peaks of the carrier waveform gives the exact shape of the modulating information signal. This imaginary line on the carrier waveform is known as the envelope.





(a) The modulating or information signal

(b) The modulated carrier

AM- Basics

The AM signal

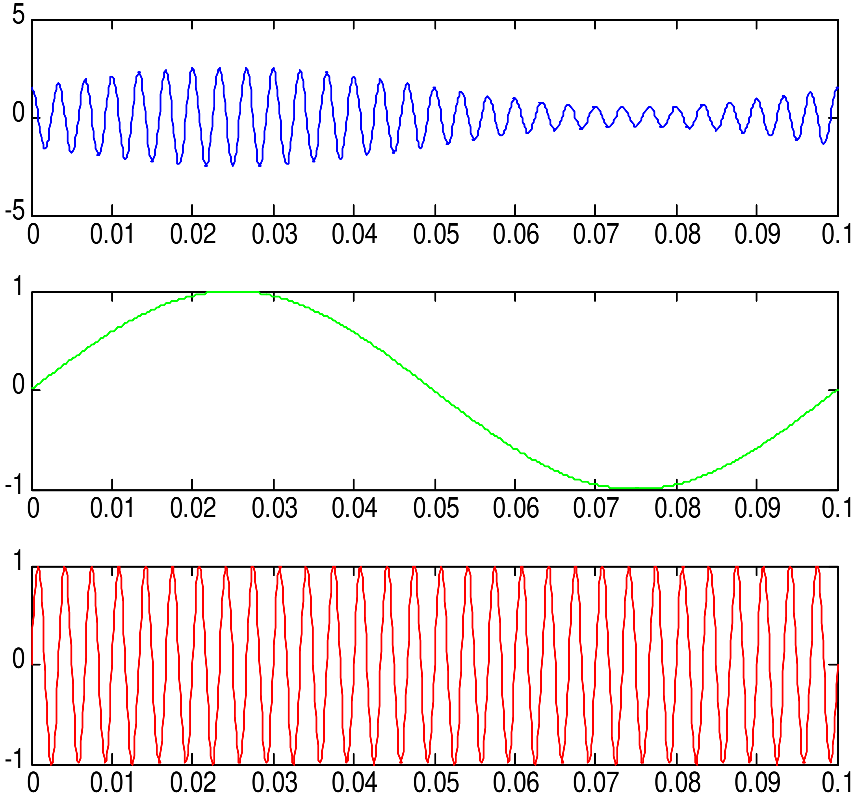
$$s(t) = A_c\left[1 + k \bullet m(t)\right]\mathbf{cos}\,\omega_c t$$

The modulating signal:

$$m(t)$$

The Carrier Signal:

$$c(t) = A_c \cos \omega_c t$$



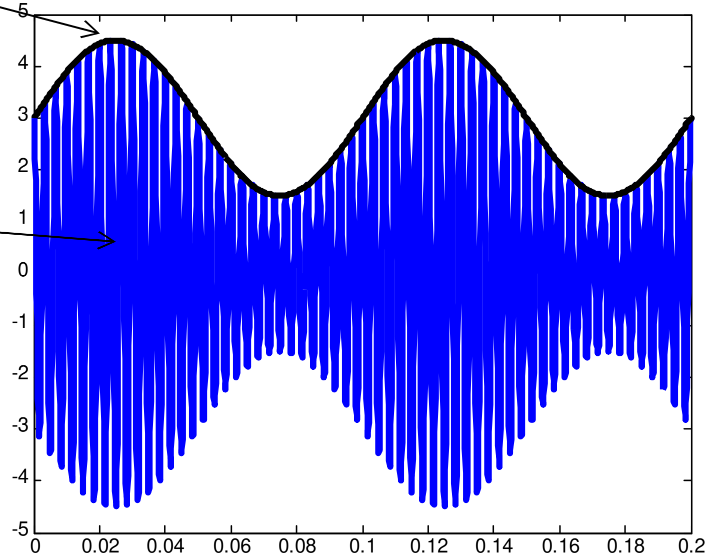
AM- Basics

The Envelope:

$$s(t) = A_c\left[1 + k \bullet m(t)\right]$$

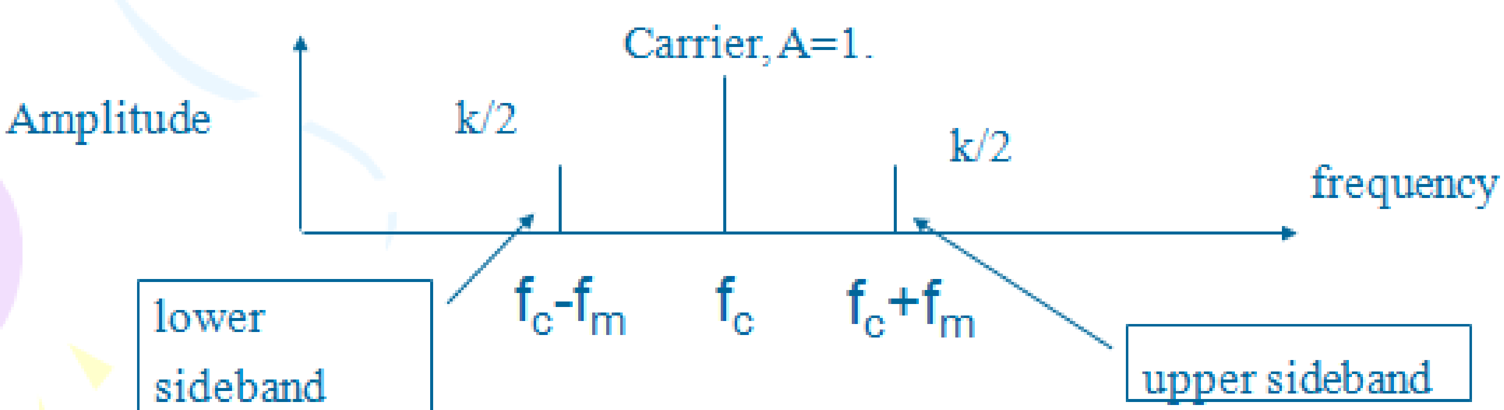
The AM Signal

$$s(t) = A_c\left[1 + k \bullet m(t)\right]\mathbf{cos}\,\omega_c t$$



Sidebands and the Frequency domain

- Whenever a carrier is modulated by an information signal, new signals at different frequencies are generated as part of the process. These new frequencies, which are called side frequencies, or sidebands, occur in the frequency spectrum directly above and directly below the carrier frequency.
- More specifically, the sidebands occur at frequencies that are the sum and difference of the carrier and modulating frequencies. When signals of more than one frequency make up a waveform, it is often better to show the AM signal in the frequency domain rather than in the time domain.
- In the frequency domain this gives:



Sidebands

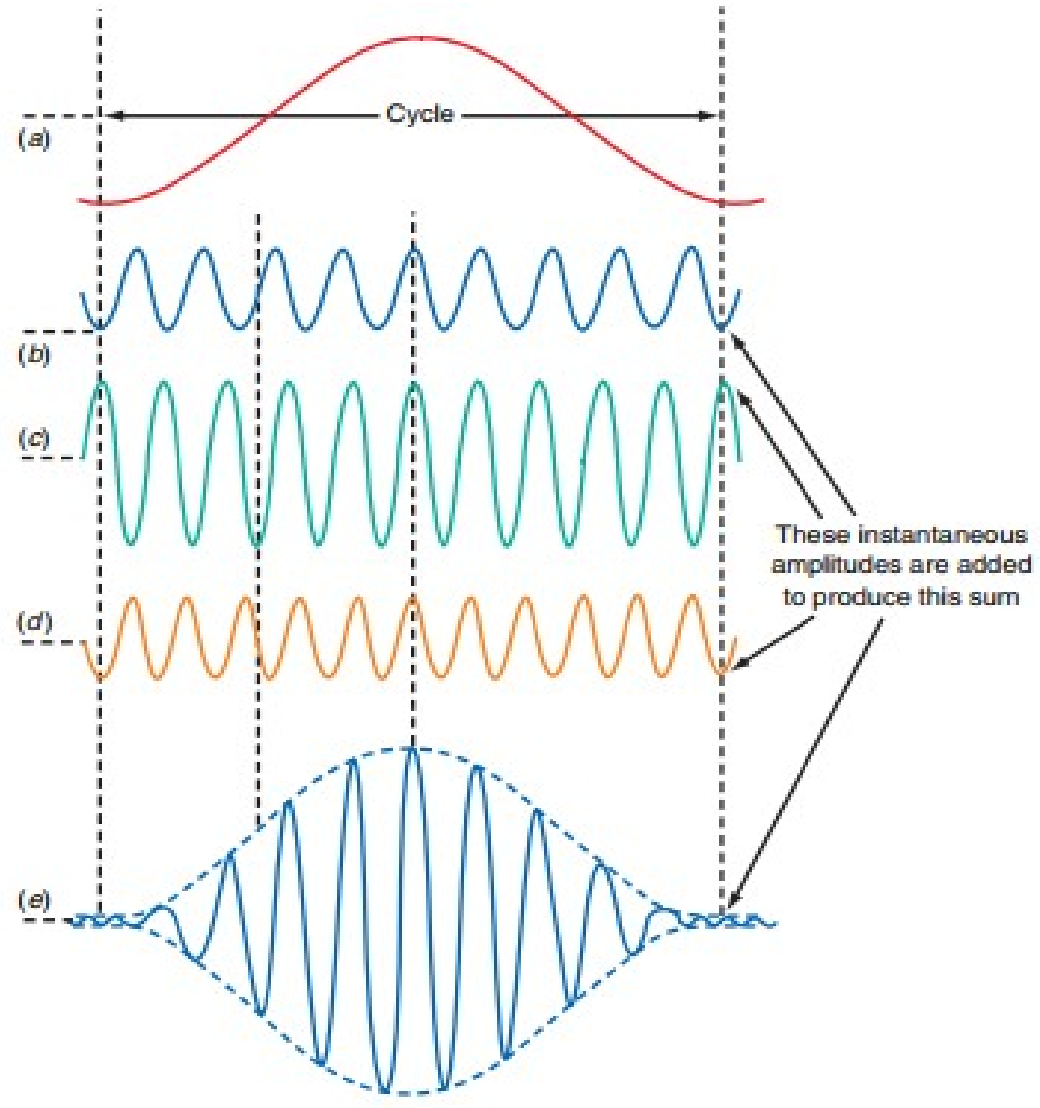
- An AM signal is the algebraic sum of the carrier and the upper and lower sideband sinewaves.

  Here, (a) modulating signal

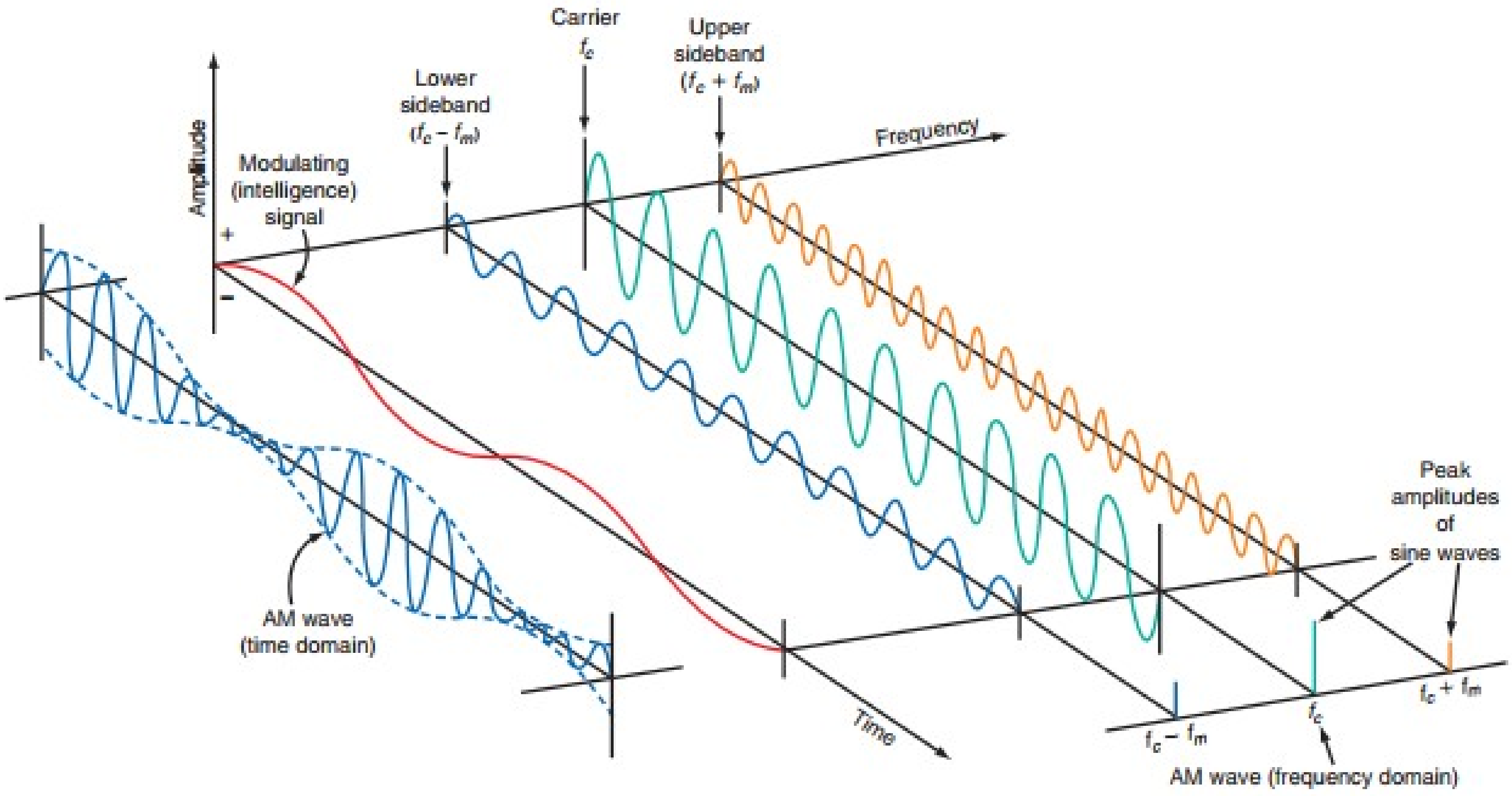
  (b) Lower sideband (c) Carrier (d) Upper sideband (e) Composite AM wave

  Observing an AM signal on an oscilloscope, you can see the amplitude variations of the carrier with respect to time. This time-domain display gives no obvious or outward indication of the existence of the sidebands.

  So it is often better to show the AM signal in the frequency domain rather than in the time domain.

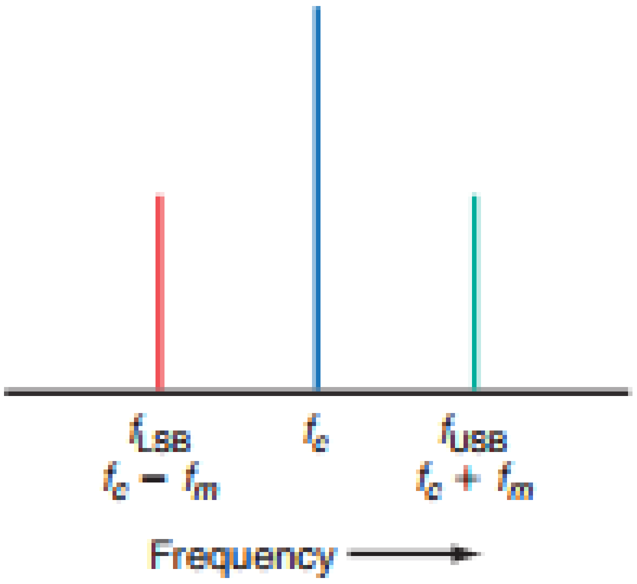


The relationship between the time and frequency domains



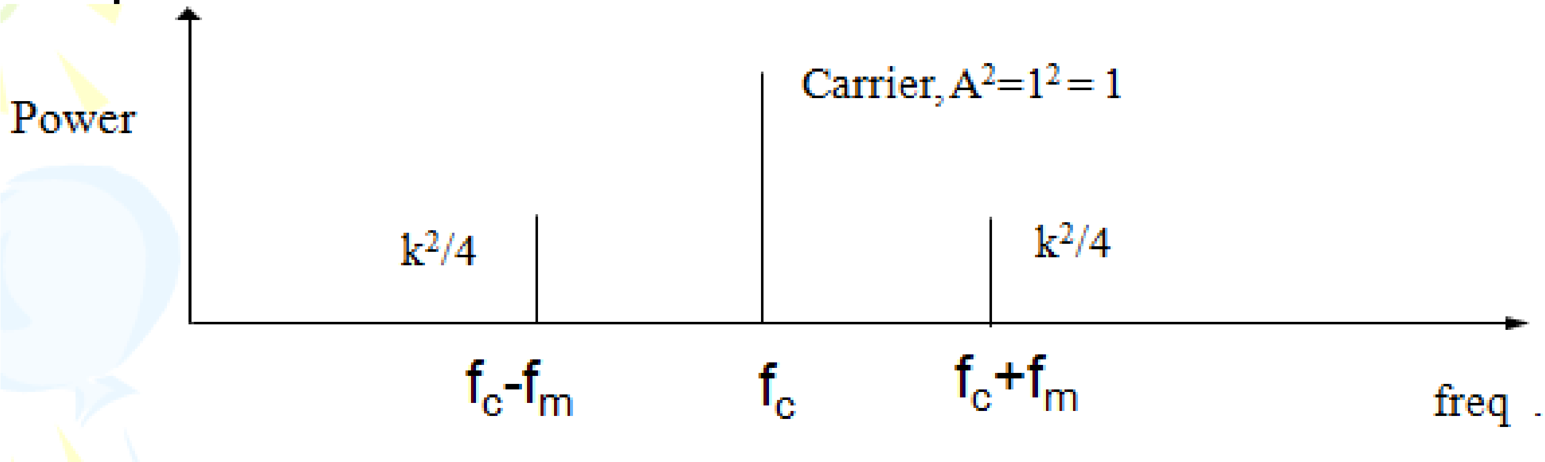
Amplitude Modulation

- The AM signal is generated using a multiplier.
- All info is carried in the amplitude of the carrier, AM carrier signal has time-varying envelope.
- In frequency domain the AM waveform are the lower-side frequency/band (f_c - f_m) , the carrier frequency f_c, the upper-side frequency/band (f_c + f_m).



AM Power frequency spectrum

- AM Power frequency spectrum obtained by squaring the amplitude:



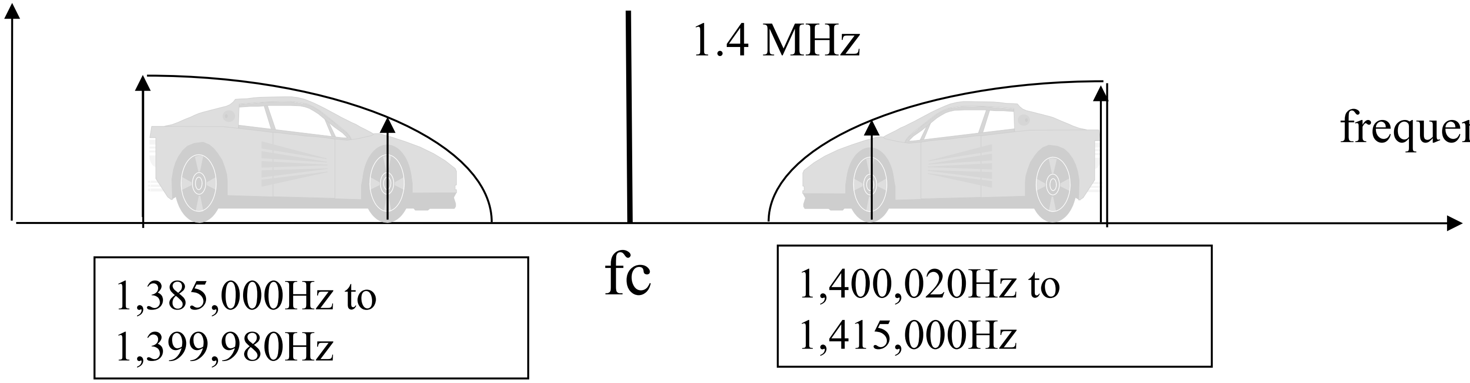
- Total power for AM:

$$= A^2 + \frac{k^2}{4} + \frac{k^2}{4}$$

$$= 1 + \frac{k^2}{2}$$

AM Modulation – Example

- The information signal is usually not a single frequency but a range of frequencies (band). For example, frequencies from 20Hz to 15KHz. If we use a carrier of 1.4MHz, what will be the AM spectrum?
- In frequency domain the AM waveform are the lower-side frequency/band (f_c - f_m), the carrier frequency f_c, the upper-side frequency/band (f_c + f_m). Bandwidth: 2x(25K-20)Hz.

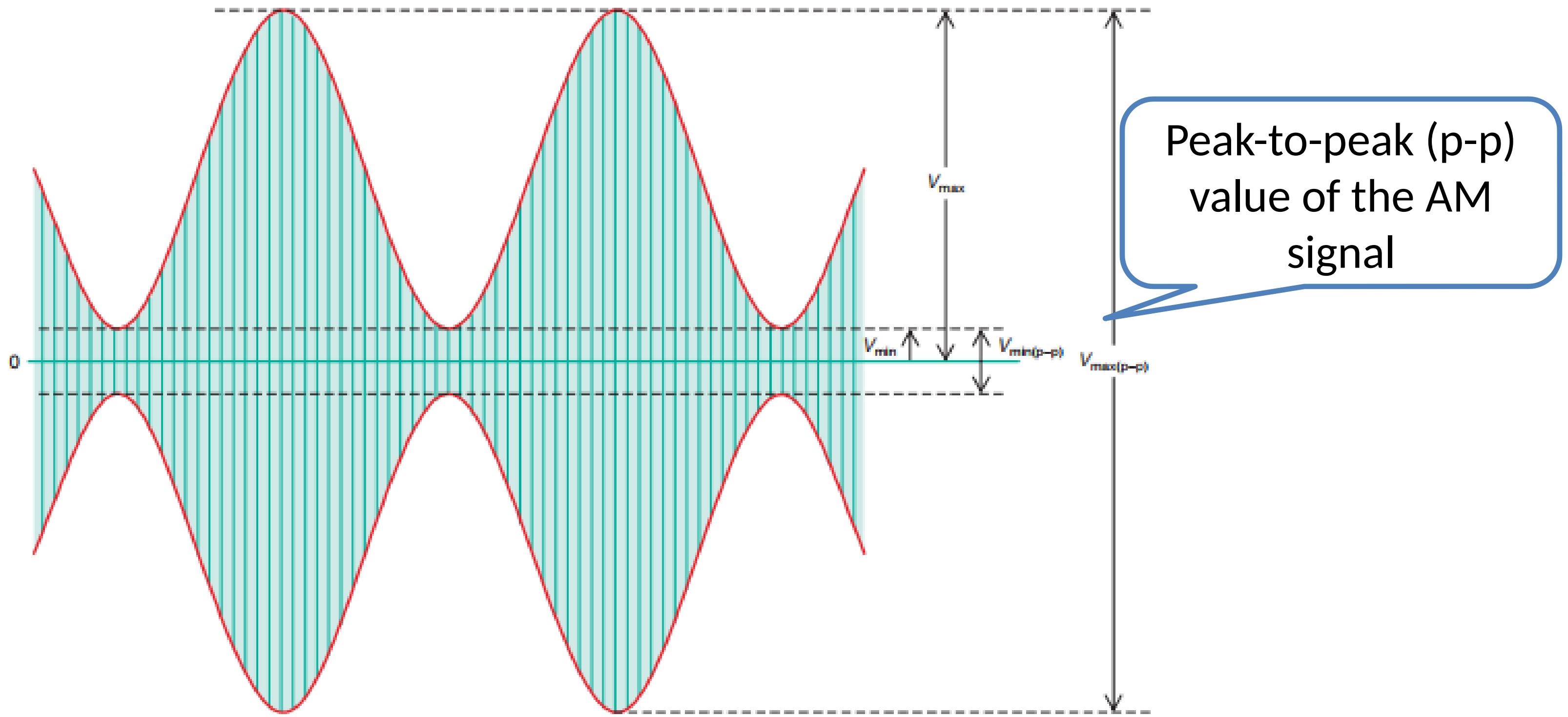


Modulation Index

- For undistorted AM to occur, the modulating signal voltage must be less than the carrier voltage.
  - Therefore the relationship between the amplitude of the modulating signal and the amplitude of the carrier signal is important. This relationship, known as the modulation index m (also called the modulating factor or coefficient, or the degree of modulation), is the ratio **$m = V_m / V_c$**
- The modulation index should be a number between 0 and 1. If the amplitude of the modulating voltage is higher than the carrier voltage, m will be greater than 1, causing distortion of the modulated waveform.
- The ideal condition for AM is when **$V_m = V_c$ or $m = 1$**, which gives 100 percent modulation. This results in the greatest output power at the transmitter and the greatest output voltage at the receiver, with no distortion

Percentage of Modulation

- The modulation index can be determined by measuring the actual values of the modulation voltage and the carrier voltage and computing the ratio.
  - However, it is more common to compute the modulation index from measurements taken on the composite modulated wave itself. When the AM signal is displayed on an oscilloscope, the modulation index can be computed from and , as shown in this figure:



Percentage of Modulation

- The peak value of the modulating signal is one-half the difference of the peak (max) and trough (min) values:

  $V_m = (V_{max} - V_{min}) / 2$
- The peak value of the carrier signal is the average of the max and min values:

  $V_c = (V_{max} + V_{min}) / 2$

- The modulation index is

  $$m = (V_{max} - V_{min}) / (V_{max} + V_{min})$$

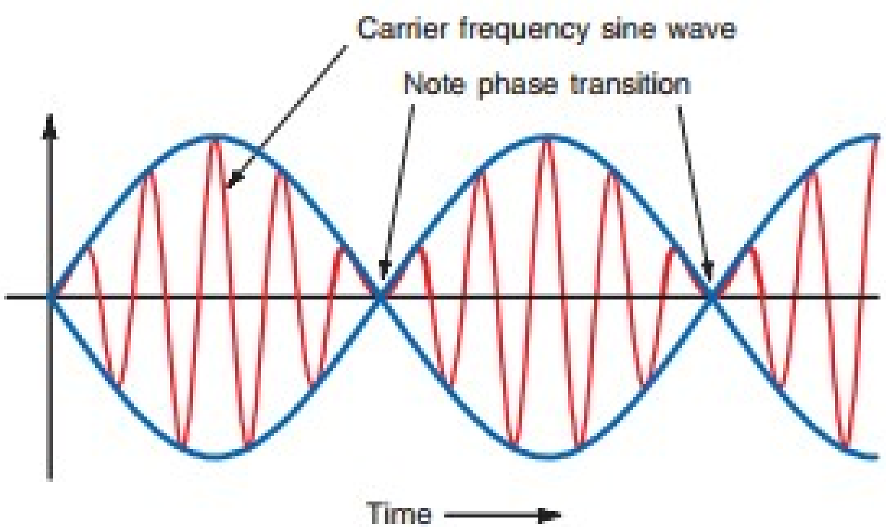
The amount, or depth, of AM is more commonly expressed as the percentage of modulation rather than as a fractional value.

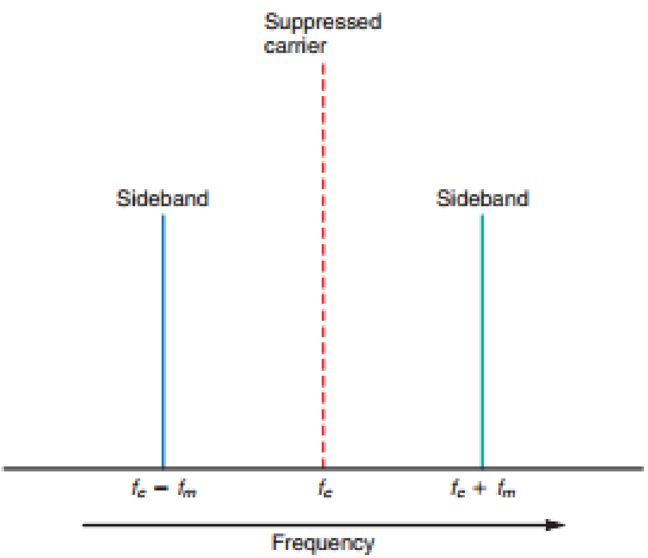
Single-Sideband Modulation

- In amplitude modulation, two-thirds of the transmitted power is in the carrier, which itself conveys no information.
- The real information is contained within the sidebands.
- One way to improve the efficiency of amplitude modulation is to suppress the carrier and eliminate one sideband.
- The result is a single-sideband (SSB) signal. SSB is a form of AM that offers unique benefits in some types of electronic communication.

Double-sideband suppressed carrier

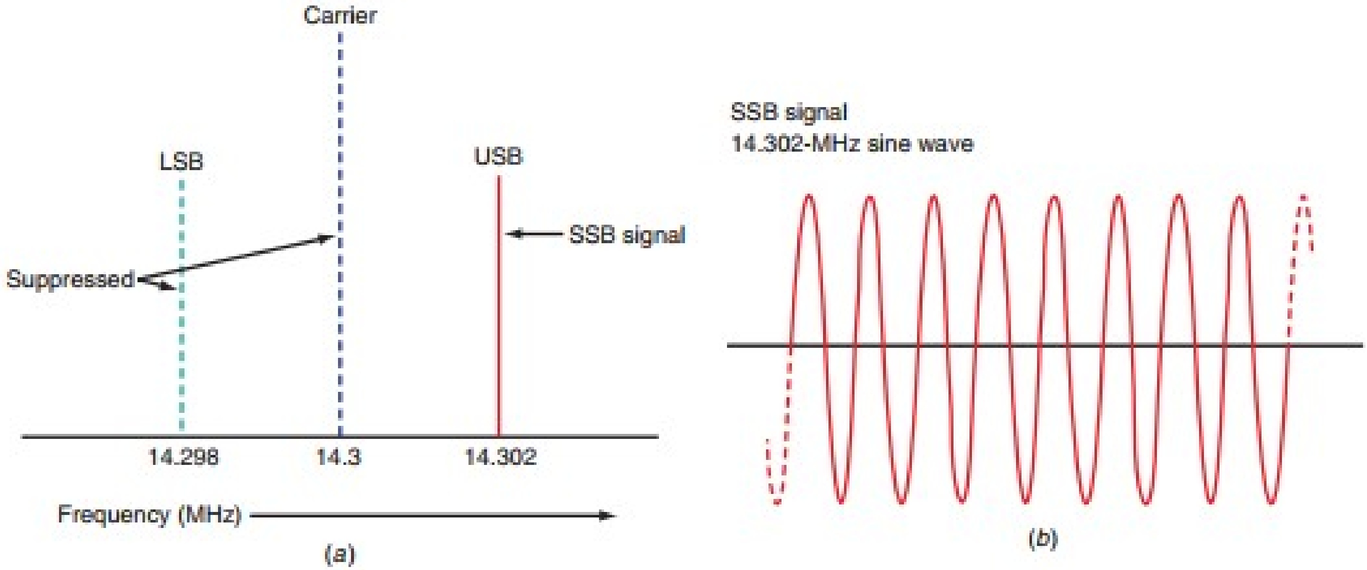
- The first step in generating an SSB signal is to suppress the carrier, leaving the upper and lower sidebands.
- This type of signal is referred to as a double-sideband suppressed carrier (DSSC or DSB) signal.
- The benefit, of course, is that no power is wasted on the carrier.
- Double-sideband suppressed carrier modulation is simply a special case of AM with no carrier as shown below (both in time domain and frequency domain





SSB Signal

- In DSB transmission, since the sidebands are the sum and difference of the carrier and modulating signals, the information is contained in both sidebands.
- As it turns out, there is no reason to transmit both sidebands in order to convey the information.
- One sideband can be suppressed; the remaining sideband is called a single-sideband suppressed carrier (SSSC or SSB) signal. An SSB signal produced by a 2-kHz sine wave modulating a 14.3-MHz sine wave carrier is shown below



Four major benefits of SSB

1. The primary benefit of an SSB signal is that the spectrum space it occupies is only one-half that of AM and DSB signals. This greatly conserves spectrum space and allows more signals to be transmitted in the same frequency range.
2. All the power previously devoted to the carrier and the other sideband can be channeled into the single sideband, producing a stronger signal that should carry farther and be more reliably received at greater distances. Alternatively, SSB transmitters can be made smaller and lighter than an equivalent AM or DSB transmitter because less circuitry and power are used.
3. Because SSB signals occupy a narrower bandwidth, the amount of noise in the signal is reduced.
4. There is less selective fading of an SSB signal over long distances. An AM signal is really multiple signals, at least a carrier and two sidebands. These are on different frequencies, so they are affected in slightly different ways by the ionosphere and upper atmosphere, which have a great influence on radio signals of less than about 50 MHz. The carrier and sidebands may arrive at the receiver at slightly different times, causing a phase shift that can, in turn, cause them to add in such a way as to cancel one another rather than add up to the original AM signal. Such cancellation, or selective fading, is not a problem with SSB since only one sideband is being transmitted.

Disadvantages of DSB and SSB

- The main disadvantage of DSB and SSB signals is that they are harder to recover, or demodulate, at the receiver.
- Demodulation depends upon the carrier being present. If the carrier is not present, then it must be regenerated at the receiver and reinserted into the signal.
- To faithfully recover the signal, the reinserted carrier must have the same phase and frequency as those of the original carrier. This is a difficult requirement.
  - When SSB is used for voice transmission, the reinserted carrier can be made variable in frequency so that it can be adjusted manually while listening to recover the signal. This is not possible with some kinds of data signals.
  - To solve this problem, a low-level carrier signal is sometimes transmitted along with the two sidebands in DSB or a single sideband in SSB. Because the carrier has a low power level, the essential benefits of SSB are retained, but a weak carrier is received so that it can be amplified and reinserted to recover the original information. Such a low-level carrier is referred to as a ***pilot carrier***. This technique is used in FM stereo transmissions as well as in the transmission of the color information in a TV picture.

Frequency Modulation

- The classic definition of FM is that the instantaneous output frequency of a transmitter is varied in accordance with the modulating signal.
- Consider again the general carrier $v_c(t) = V_c \cos(\omega_c t + \varphi_c)$
  $(\omega_c t + \varphi_c)$ represents the angle of the carrier.
- There are two ways of varying the angle of the carrier.
  a) By varying the frequency, f_c – **Frequency Modulation.**
  b) By varying the phase, ψ_c – **Phase Modulation**
- The **modulation index** for FM is defined as follows: m= δ/f_m
- **frequency deviation** (δ)
  – The amount of frequency deviation a signal experiences is a measure of the change in transmitter output frequency from the rest frequency of the transmitter. The rest frequency of a transmitter is defined as the output frequency with no modulating signal applied.
- **Modulating Frequency** (f_m) causes the deviations

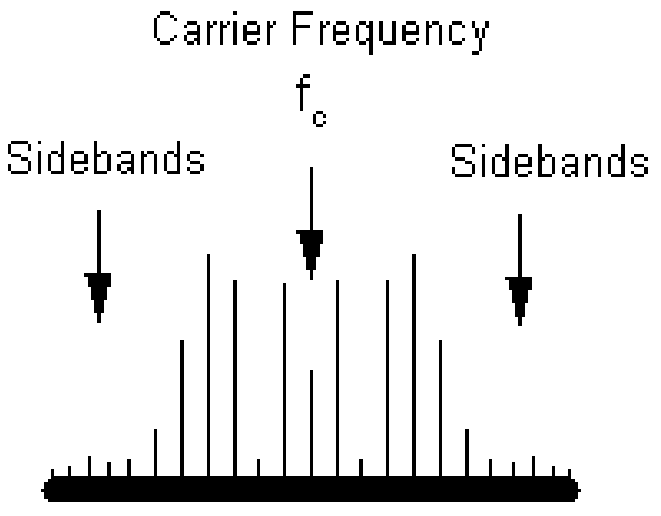
Frequency-domain expression of FM

- The time domain representation of the FM signal can be converted to an equivalent frequency-domain expression that includes the carrier and sidebands.
- The $J_n(x)$ functions are known as **Bessel Functions** of First kind. Graphs of $J_n(x)$ look like slowly decreasing sine and cosine functions. The $J_n(x)$ functions are a closely related family of functions in the same way that sin(nx) and cos(nx) for a family of similar functions.
- The zeroth order Bessel Functions, $J_0(m)$ determines the amplitude of the carrier. The nth Bessel function $J_n(m)$ determines the amplitude of the nth pair of sidebands.

$$\begin{aligned} V(t) = {} & J_0(m)\cos(2\pi f_c t) - J_1(m)\left[\cos(2\pi(f_c - f_m)t) + \cos(2\pi(f_c + f_m)t)\right] \\ & + J_2(m)\left[\cos(2\pi(f_c - 2f_m)t) + \cos(2\pi(f_c + 2f_m)t)\right] \\ & - J_3(m)\left[\cos(2\pi(f_c - 3f_m)t) + \cos(2\pi(f_c + 3f_m)t)\right] + \ldots \end{aligned}$$

Two important concepts contained in the expression

- The amplitude of the carrier depends on m. the modulation index. This is quite different from AM, where the amplitude of the carrier was independent of the value of m.
- There are an infinite number of sidebands. Thus the theoretical bandwidth of FM is infinite.
  - An infinite bandwidth signal would be very difficult to transmit. Fortunately, the higher order sidebands in FM have extremely low amplitude and may be ignored.

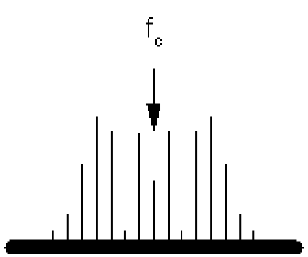


FM applications

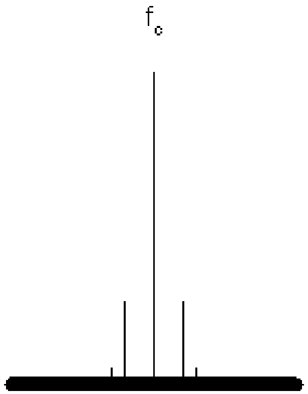
- FM applications are divided into two broad categories:
  - Wideband FM (WFM): has a large number (theoretically infinite) number of sidebands.
  - Narrowband FM (NBFM): has only a single pair of significant sidebands.
- The primary difference between the two types of FM is the number of sidebands in the modulated signal.
- It is possible to determine if a particular FM signal will be wide or narrow band by looking at a quantity called the Deviation Ratio (DR). It is defined as the ratio of the maximum deviation of the FM signal to the maximum modulating frequency: $DR = \delta / f_{max}$
- The DR is also the modulation index of the highest modulating frequency. If the $DR \geq 1.0$ it is called wideband FM (WFM) and $DR < 1.0$ the modulation is narrow band FM (NBFM).

WBFM vs NBFM

- One of the drawbacks of wideband FM is the large bandwidth required. Commercial FM broadcasting requires 150 KHz of bandwidth to transmit a15 KHz audio signal, 5 times the bandwidth required for an AM signal.
  - The DR for commercial FM broadcasting is 75/15 = 5.0. This is clearly a wideband FM signal.
- **NBFM** is widely used in business and public service communications. The DR for NBFM is restricted to values between 0.5 and 1.0. By holding the DR to such small values, only the carrier and the first sideband are of significant amplitude. When only one sideband and the carrier are transmitted, the NBFM signal occupies the same bandwidth as an AM signal. This overcomes one of the drawbacks of wideband FM, the large bandwidth required.

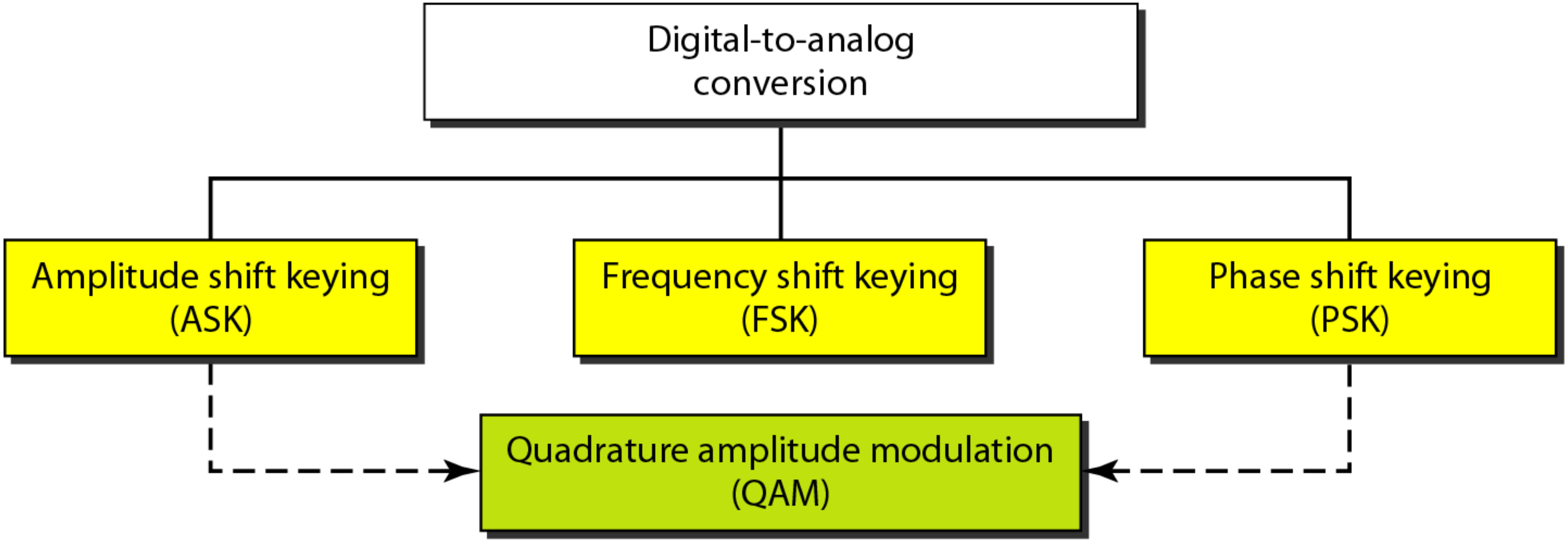


Wideband FM



Narrowband FM

Types of digital to analog conversion



Data rate versus Signal rate

- Bit rate, N, is the number of bits per second (bps).
- Baud rate is the number of signal elements per second (bauds).
- In the analog transmission of digital data, the signal or baud rate is less than or equal to the bit rate.

  S=Nx1/r bauds

  Where r is the number of data bits per signal element.

Problem

- An analog signal carries 4 bits per signal element. If 1000 signal elements are sent per second, find the bit rate.
- Solution
  - In this case, r = 4, S = 1000, and N is unknown. We can find the value of N from

$$S = N \times \frac{1}{r} \qquad \text{or} \qquad N = S \times r = 1000 \times 4 = 4000 \text{ bps}$$

- *An analog signal has a bit rate of 8000 bps and a baud rate of 1000 baud. How many data elements are carried by each signal element? How many signal elements do we need?*
- *Solution*
  - *In this example, S = 1000, N = 8000, and r and L are unknown. We find first the value of r and then the value of L.*

$$S = N \times \frac{1}{r} \quad \Rightarrow \quad r = \frac{N}{S} = \frac{8000}{1000} = 8 \text{ bits/baud}$$

$$r = \log_2 L \quad \Rightarrow \quad L = 2^r = 2^8 = 256$$

Amplitude Shift Keying (ASK)

- ASK is implemented by changing the amplitude of a carrier signal to reflect amplitude levels in the digital signal.
- For example: a digital “1” could not affect the signal, whereas a digital “0” would, by making it zero.
- The line encoding will determine the values of the analog waveform to reflect the digital data being carried.

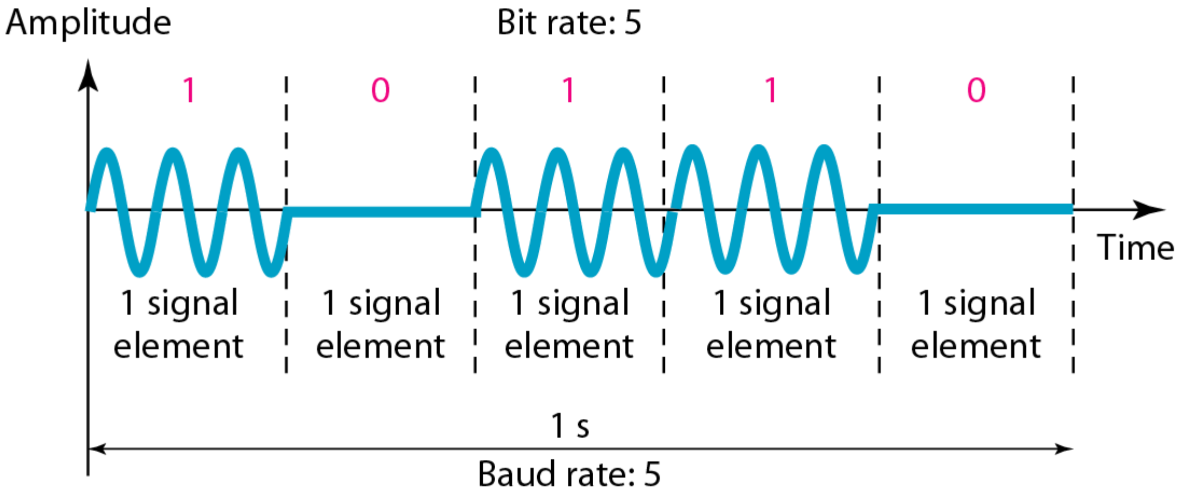
Bandwidth of ASK

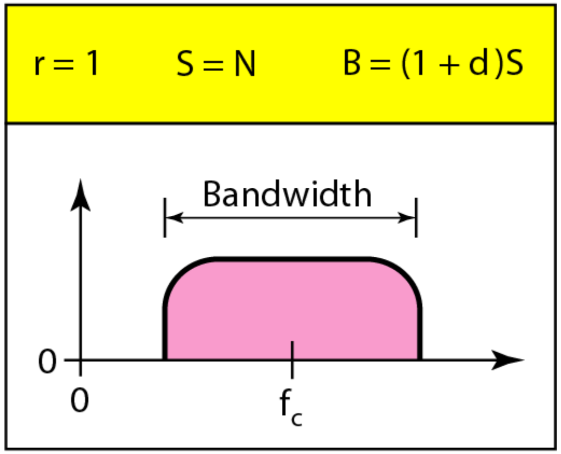
- The bandwidth B of ASK is proportional to the signal rate S.

$$B = (1+d)S$$

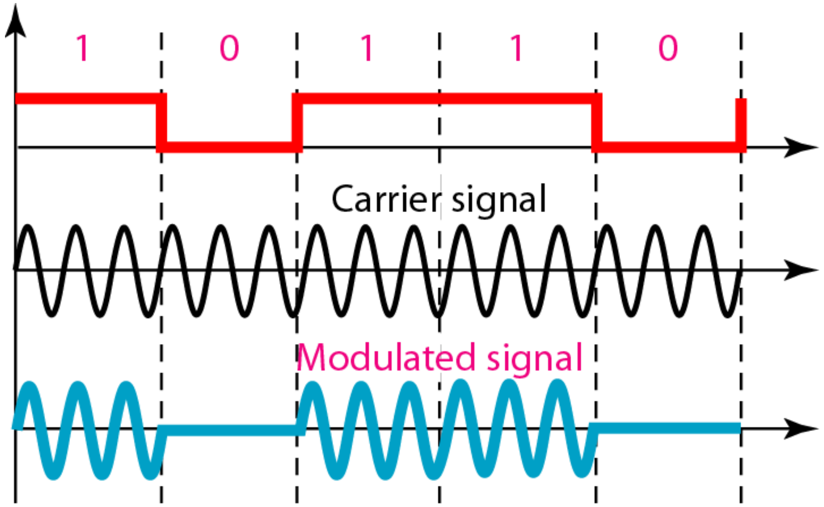
- “d” is due to modulation and filtering, lies between 0 and 1.

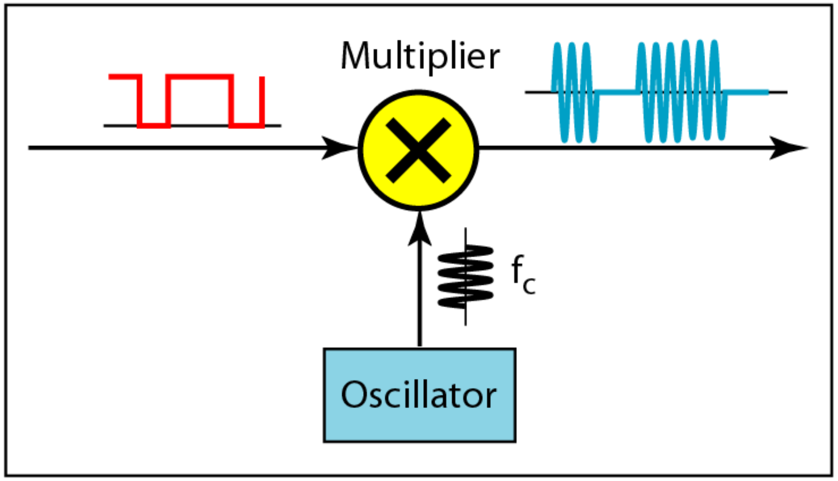
Binary amplitude shift keying





Implementation of Binary ASK





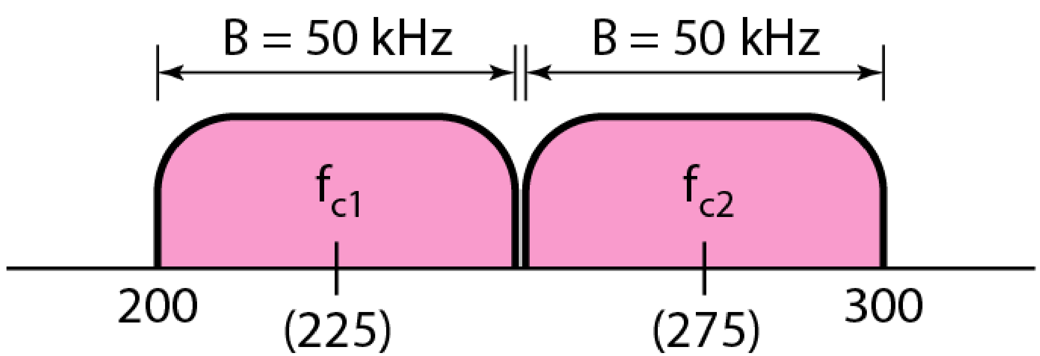
Problem

- We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What are the carrier frequency and the bit rate if we modulated our data by using ASK with d = 1?
- Solution
  - The middle of the bandwidth is located at 250 kHz. This means that our carrier frequency can be at f_c = 250 kHz. We can use the formula for bandwidth to find the bit rate (with d = 1 and r = 1).

$$\boxed{B = (1+d) \times S = 2 \times N \times \frac{1}{r} = 2 \times N = 100 \text{ kHz} \quad \longrightarrow \quad N = 50 \text{ kbps}}$$

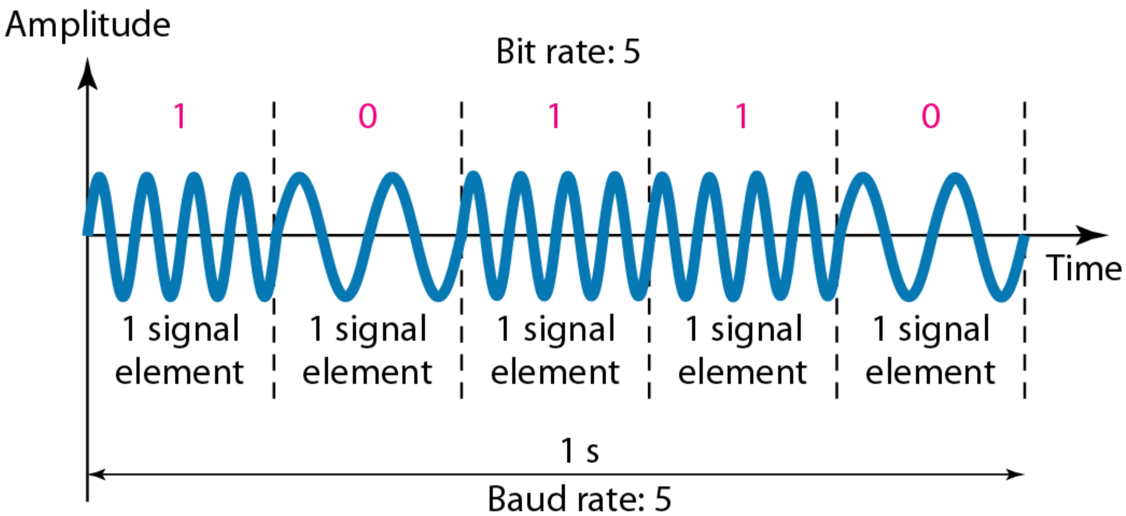
Example

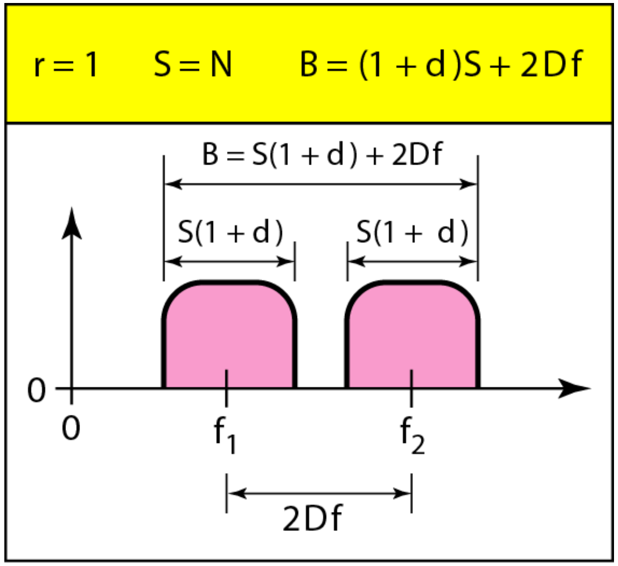
- In data communications, we normally use full-duplex links with communication in both directions. We need to divide the bandwidth into two with two carrier frequencies, as shown in figure below. The figure shows the positions of two carrier frequencies and the bandwidths. The available bandwidth for each direction is now 50 kHz, which leaves us with a data rate of 25 kbps in each direction.



Frequency Shift Keying

- The digital data stream changes the frequency of the carrier signal, f_c.
- For example, a "1" could be represented by f_1 and a "0" could be represented by f_2





- If the difference between the two frequencies (f_1 and f_2) is 2Df then the required BW B will be:

$$B = (1+d)xS + 2Df$$

Problem

- We have an available bandwidth of 100 kHz which spans from 200 to 300 kHz. What should be the carrier frequency and the bit rate if we modulated our data by using FSK with d = 1?

- Solution
  - This problem is similar to Example 5.3, but we are modulating by using FSK. The midpoint of the band is at 250 kHz. We choose $2\Delta f$ to be 50 kHz; this means

$$\boxed{B = (1+d) \times S + 2\Delta f = 100 \quad \longrightarrow \quad 2S = 50 \text{ kHz} \quad S = 25 \text{ kbaud} \quad N = 25 \text{ kbps}}$$

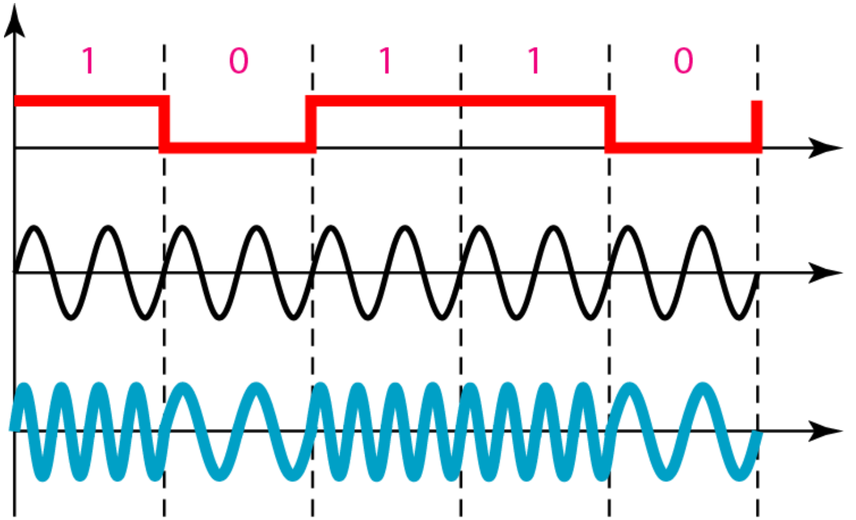
Coherent and Non Coherent

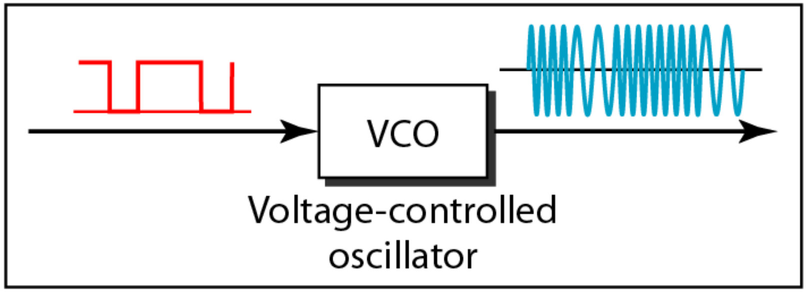
- In a non-coherent FSK scheme, when we change from one frequency to the other, we do not adhere to the current phase of the signal.
- In coherent FSK, the switch from one frequency signal to the other only occurs at the same phase in the signal.

Multi level FSK

- Similarly to ASK, FSK can use multiple bits per signal element.
- That means we need to provision for multiple frequencies, each one to represent a group of data bits.
- The bandwidth for FSK can be higher

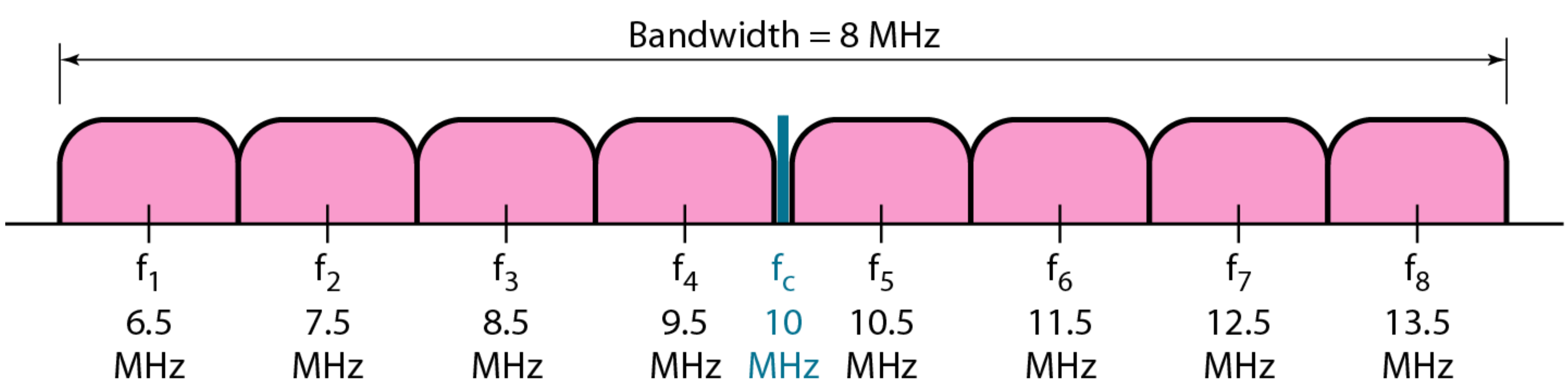
$$B = (1+d)xS + (L-1)/2Df = LxS$$





Problem

- We need to send data 3 bits at a time at a bit rate of 3 Mbps. The carrier frequency is 10 MHz. Calculate the number of levels (different frequencies), the baud rate, and the bandwidth.
- Solution
  - We can have $L = 2^3 = 8$. The baud rate is $S = 3$ Mbps/3 = 1 Mbaud. This means that the carrier frequencies must be 1 MHz apart ($2\Delta f = 1$ MHz). The bandwidth is $B = 8 \times 1M = 8M$. Figure below shows the allocation of frequencies and bandwidth.

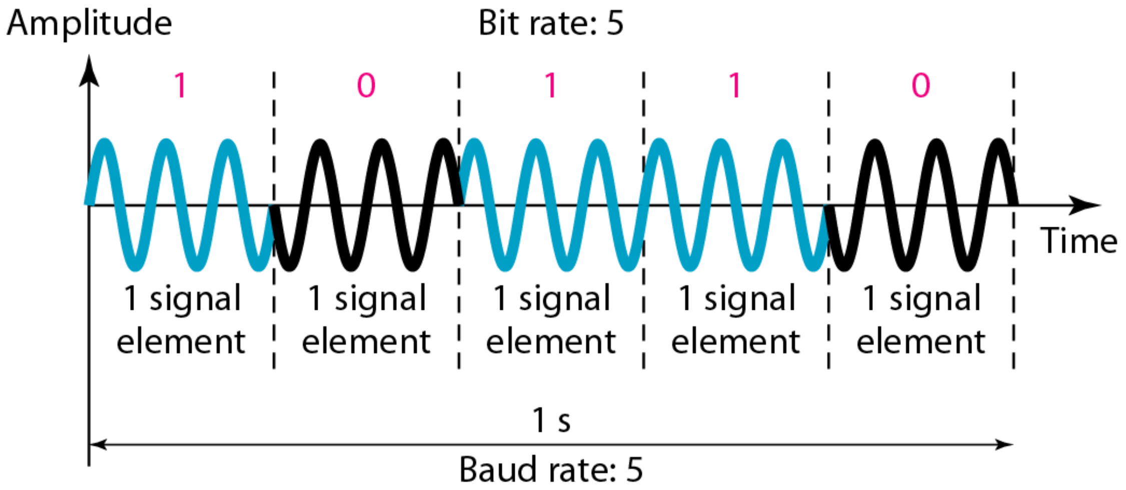


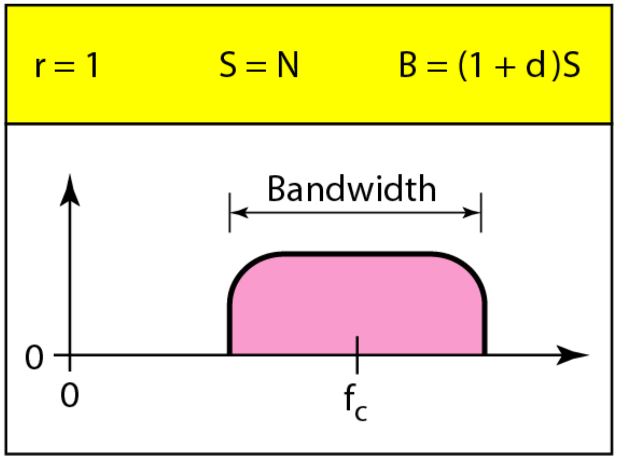
Phase Shift Keyeing

- We vary the phase shift of the carrier signal to represent digital data.
- The bandwidth requirement, B is:

$$B = (1+d) \times S$$

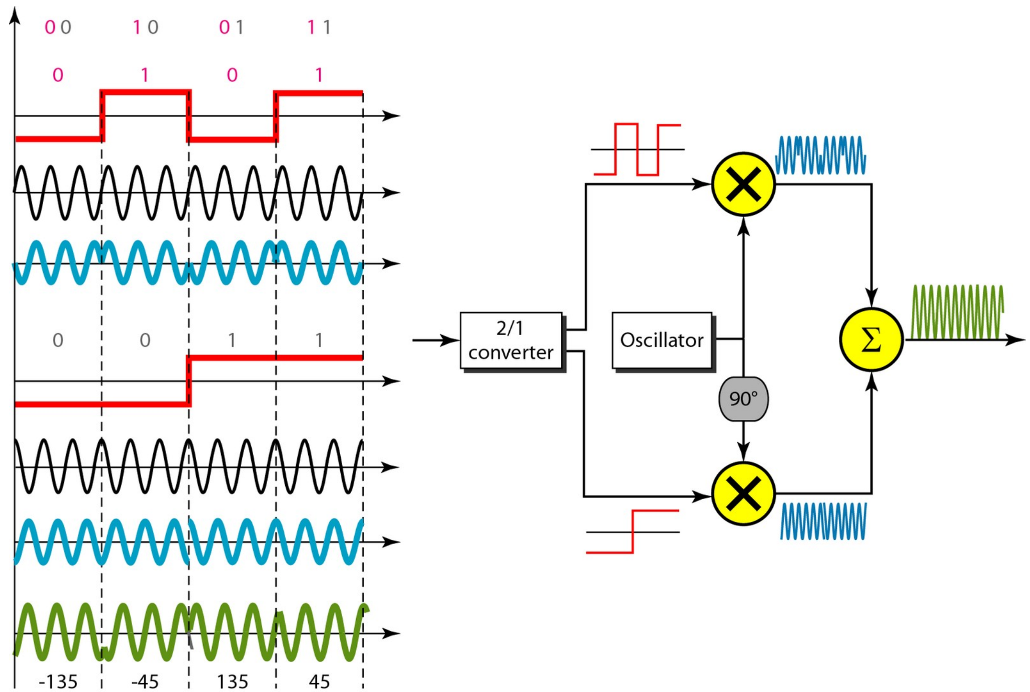
- PSK is much more robust than ASK as it is not that vulnerable to noise, which changes amplitude of the signal.





Quadrature PSK

- To increase the bit rate, we can code 2 or more bits onto one signal element.
- In QPSK, we parallelize the bit stream so that every two incoming bits are split up and PSK a carrier frequency. One carrier frequency is phase shifted 90^{o} from the other - in quadrature.
- The two PSKed signals are then added to produce one of 4 signal elements. L = 4 here.

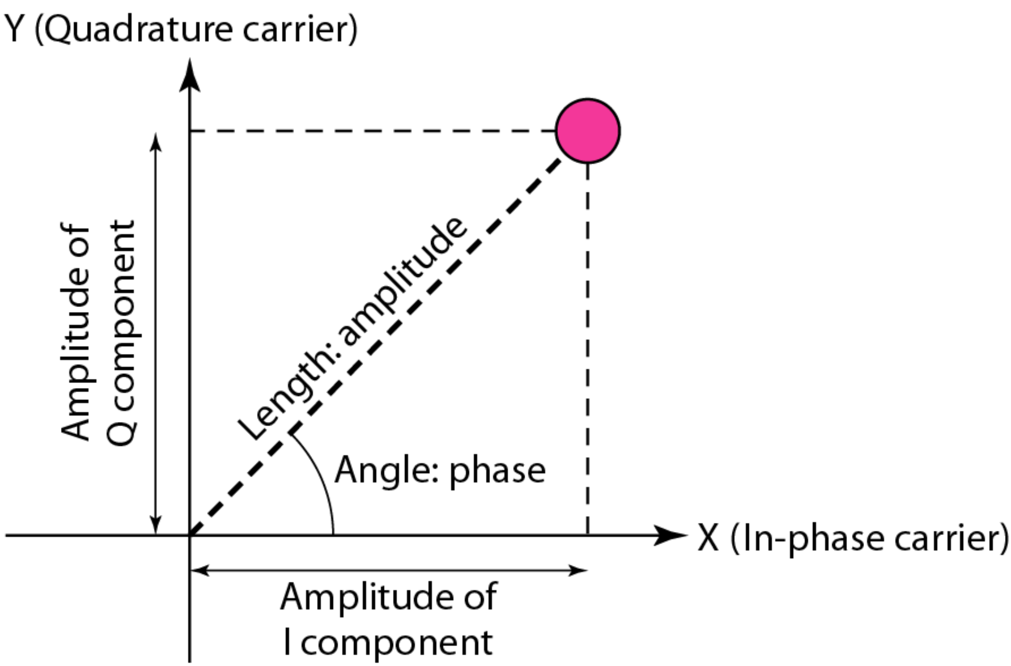


Problem

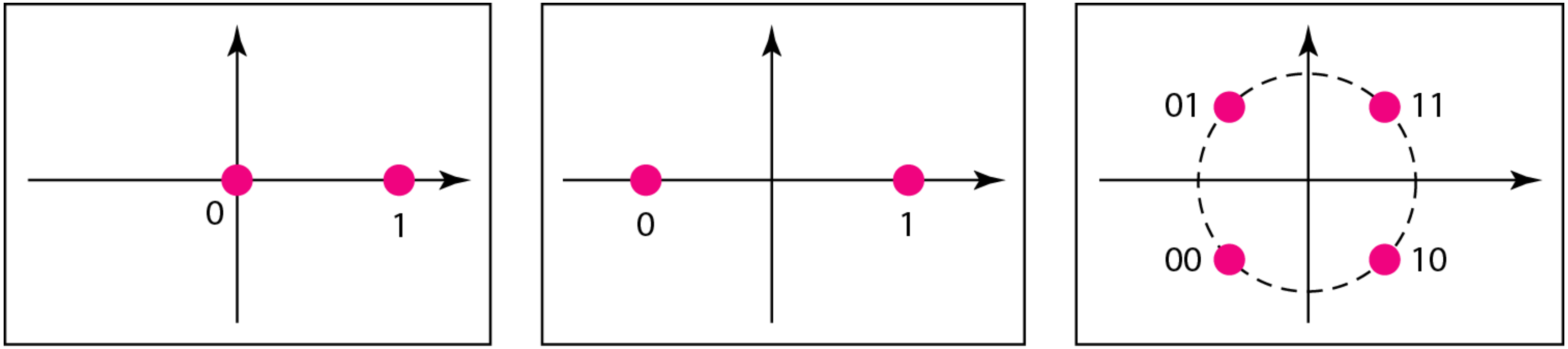
- Find the bandwidth for a signal transmitting at 12 Mbps for QPSK. The value of d = 0.
- Solution
  - For QPSK, 2 bits is carried by one signal element. This means that r = 2. So the signal rate (baud rate) is $S = N \times (1/r) = 6$ Mbaud. With a value of d = 0, we have $B = S = 6$ MHz.

Constellation Diagrams

- A constellation diagram helps us to define the amplitude and phase of a signal when we are using two carriers, one in quadrature of the other.
- The X-axis represents the in-phase carrier and the Y-axis represents quadrature carrier.



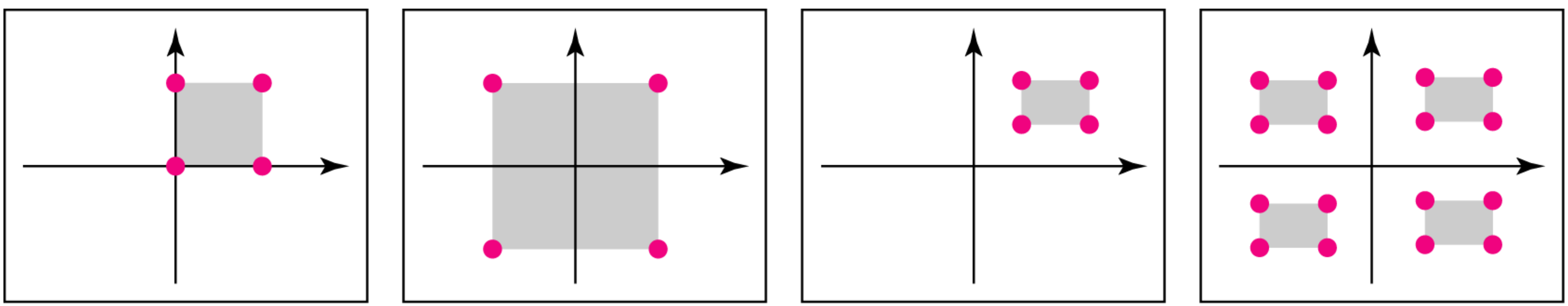
- *Show the constellation diagrams for an ASK (OOK), BPSK, and QPSK signals.*



a. ASK (OOK) b. BPSK c. QPSK

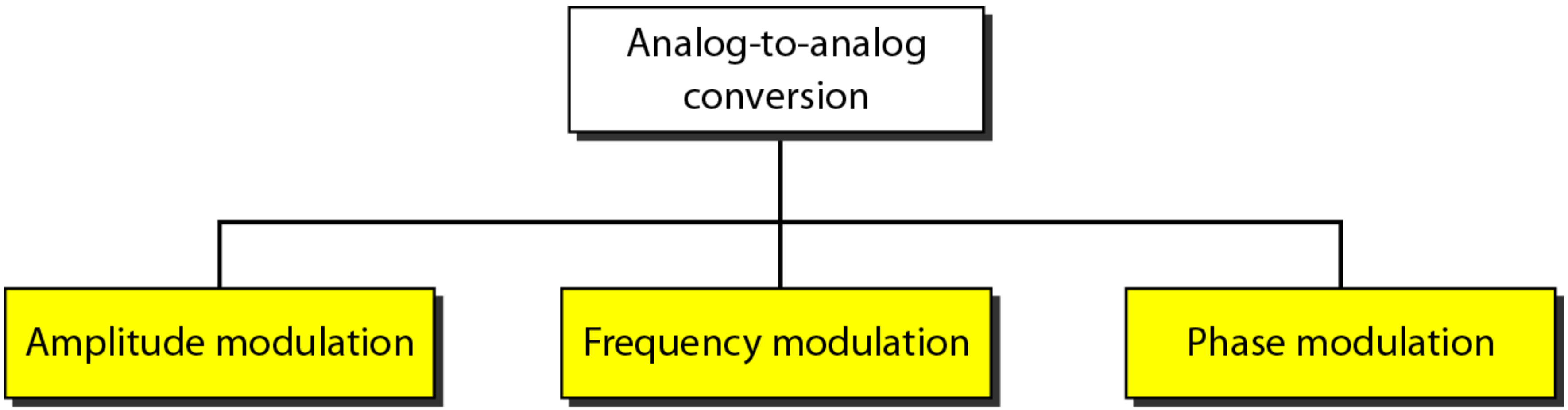
Quadrature Amplitude Modulation

- Quadrature amplitude modulation is a combination of ASK and PSK.



a. 4-QAM b. 4-QAM c. 4-QAM d. 16-QAM

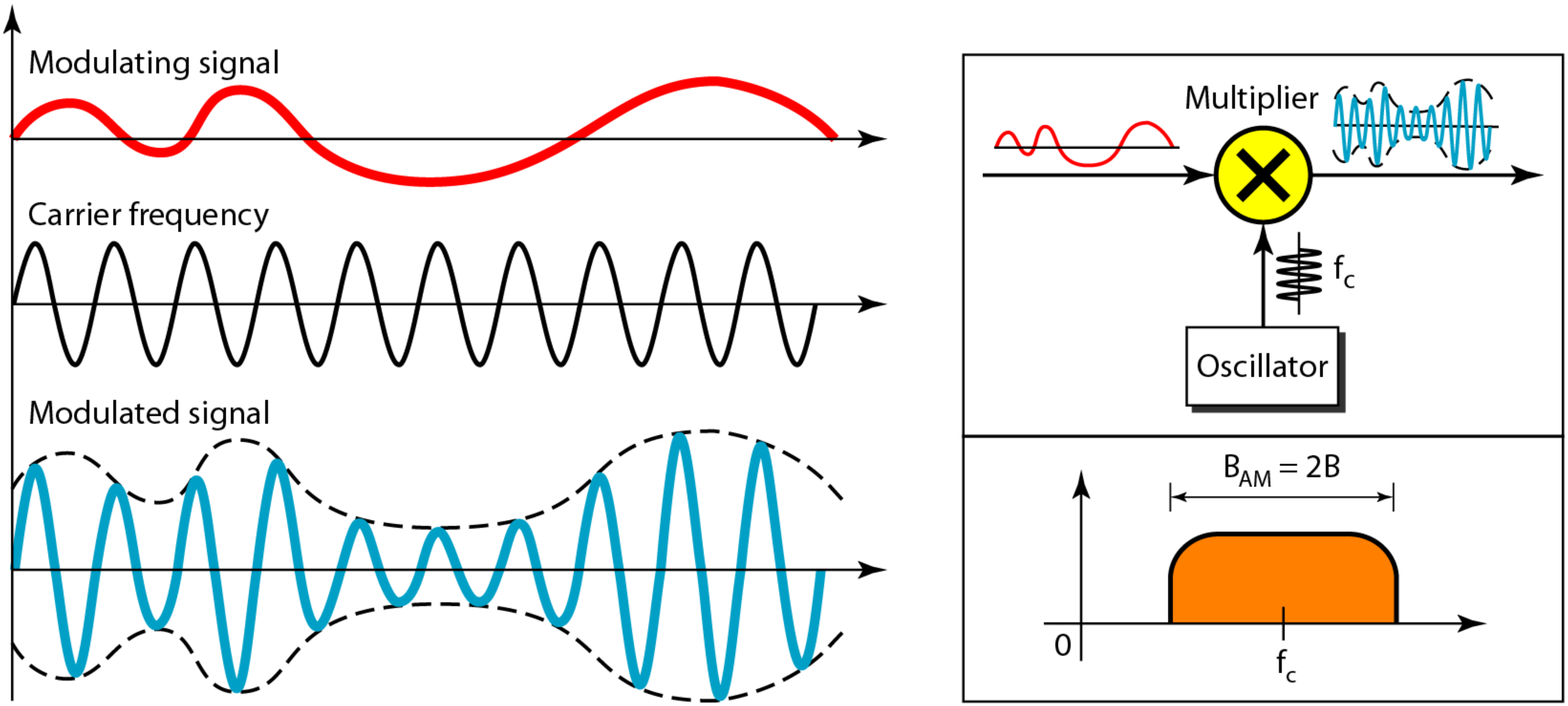
Analog to Analog



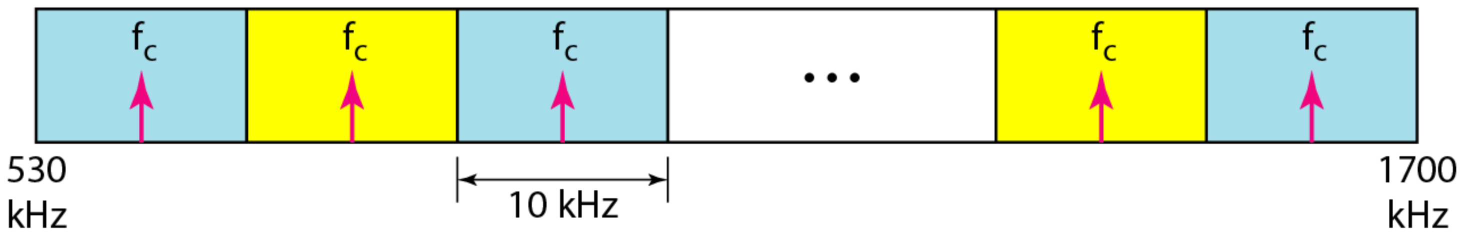
Amplitude Modulation

- A carrier signal is modulated only in amplitude value
- The modulating signal is the envelope of the carrier
- The required bandwidth is 2B, where B is the bandwidth of the modulating signal
- Since on both sides of the carrier freq. f_c, the spectrum is identical, we can discard one half, thus requiring a smaller bandwidth for transmission.

Amplitude Modulation



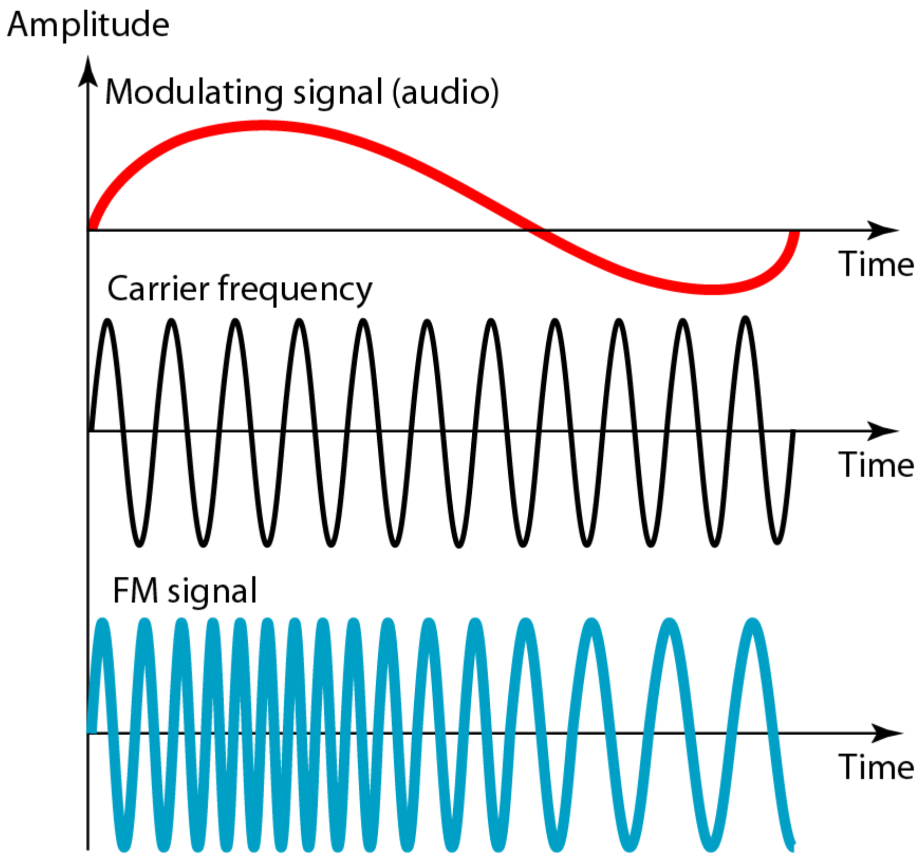
AM Band Allocation

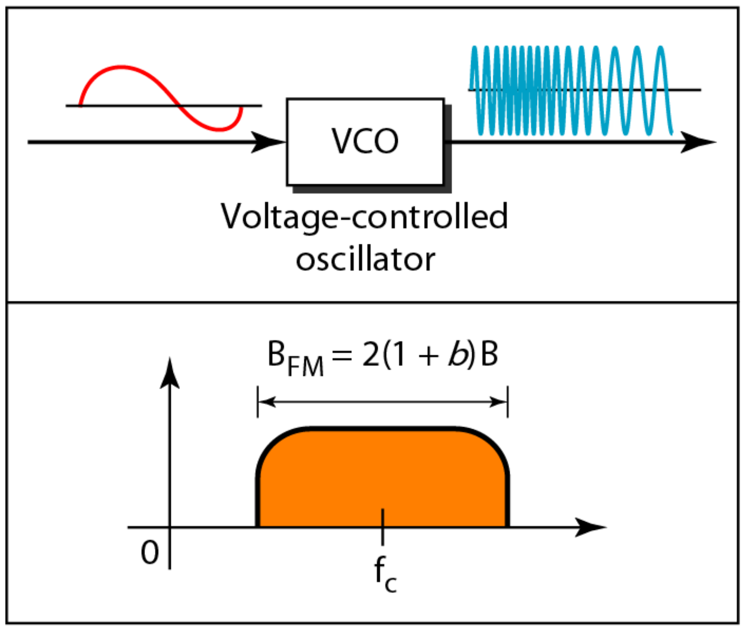


Frequency Modulation

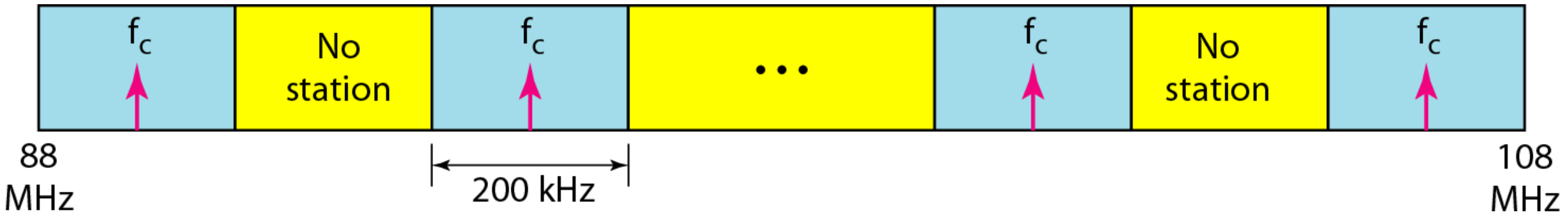
- The modulating signal changes the freq. f_c of the carrier signal
- The bandwidth for FM is high
- It is approx. 10x the signal frequency

Frequency Modulation





FM band allocation



Phase Modulation (PM)

- The modulating signal only changes the phase of the carrier signal.
- The phase change manifests itself as a frequency change but the instantaneous frequency change is proportional to the derivative of the amplitude.
- The bandwidth is higher than for AM.

Phase Modulation