



Frequency Modulation

[Objectives](#)

[Basic System](#)

[Modulation](#)

[FM](#)

[FM Spectrum](#)

[FM Performance: Bandwidth, Efficiency, and Noise](#)

[Summary](#)

Objectives

1. Know the relationship of carrier frequency, modulation frequency and modulation index to efficiency and bandwidth
2. Compare FM systems to AM systems with regard to efficiency, bandwidth and noise.

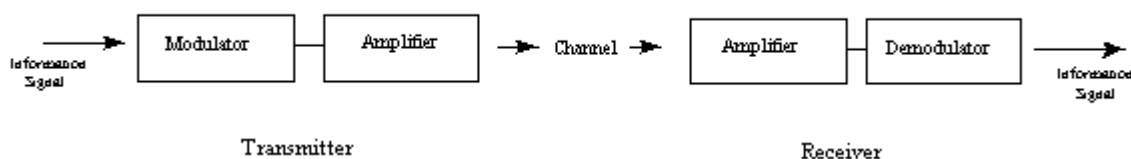
Basic System

The basic communications system has:

Transmitter: *The sub-system that takes the information signal and processes it prior to transmission. The transmitter modulates the information onto a carrier signal, amplifies the signal and broadcasts it over the channel*

Channel: *The medium which transports the modulated signal to the receiver. Air acts as the channel for broadcasts like radio. May also be a wiring system like cable TV or the Internet.*

Receiver: *The sub-system that takes in the transmitted signal from the channel and processes it to retrieve the information signal. The receiver must be able to discriminate the signal from other signals which may using the same channel (called tuning), amplify the signal for processing and demodulate (remove the carrier) to retrieve the information. It also then processes the information for reception (for example, broadcast on a loudspeaker).*



Modulation

The information signal can rarely be transmitted as is, it must be processed. In order to use electromagnetic transmission, it must first be converted from audio into an electric signal. The conversion is accomplished by a *transducer*. After conversion it is used to modulate a carrier signal.

A carrier signal is used for two reasons:

- To reduce the wavelength for efficient transmission and reception (the optimum antenna size is $\frac{1}{2}$ or $\frac{1}{4}$ of a wavelength). A typical audio frequency of 3000 Hz will have a wavelength of 100 m and would need an effective antenna length of 25 m! By comparison, a typical carrier for FM is 100 MHz, with a wavelength of 3 m, and could use an antenna only 80 cm long.
- To allow simultaneous use of the same channel, called *multiplexing*. Each unique signal can be assigned a different carrier frequency (like radio stations) and still share the same channel. The phone company actually invented modulation to allow phone conversations to be transmitted over common lines.

The process of modulation means to systematically use the information signal (what you want to transmit) to vary some parameter of the carrier signal. The carrier signal is usually just a simple, single-frequency sinusoid (varies in time like a sine wave).

The basic sine wave goes like $V(t) = V_o \sin(2\pi f t + \phi)$ where the parameters are defined below:

$V(t)$ the voltage of the signal as a function of time.

V_o the amplitude of the signal (represents the maximum value achieved each cycle)

f the frequency of oscillation, the number of cycles per second (also known as Hertz = 1 cycle per second)

ϕ the phase of the signal, representing the starting point of the cycle.

To modulate the signal just means to systematically vary one of the three parameters of the signal: amplitude, frequency or phase. Therefore, the type of modulation may be categorized as either

AM: amplitude modulation

FM: frequency modulation or

PM: phase modulation

Note: PM may be an unfamiliar term but is commonly used. The characteristics of PM are very similar to FM and so the terms are often used interchangeably.

FM

Frequency modulation uses the information signal, $V_m(t)$ to vary the carrier frequency within some small range about its original value. Here are the three signals in mathematical form:

- Information: $V_m(t)$
- Carrier: $V_c(t) = V_{co} \sin(2\pi f_c t + \phi)$
- FM: $V_{FM}(t) = V_{co} \sin(2\pi [f_c + (\Delta f/V_{mo}) V_m(t)] t + \phi)$

We have replaced the carrier frequency term, with a time-varying frequency. We have also introduced a new term: Δf , the *peak frequency deviation*. In this form, you should be able to see that the carrier frequency term: $f_c + (\Delta f/V_{mo}) V_m(t)$ now varies between the extremes of $f_c - \Delta f$ and $f_c + \Delta f$. The interpretation of Δf becomes

clear: it is the farthest away from the original frequency that the FM signal can be. Sometimes it is referred to as the "swing" in the frequency.

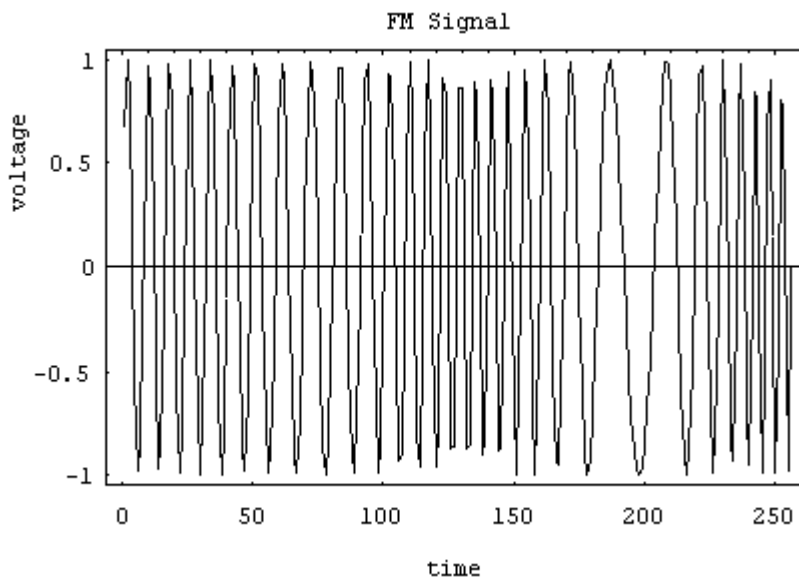
We can also define a modulation index for FM, analogous to AM:

$$\beta = \Delta f / f_m, \text{ where } f_m \text{ is the maximum modulating frequency used.}$$

The simplest interpretation of the modulation index, β , is as a measure of the peak frequency deviation, Δf . In other words, β represents a way to express the peak deviation frequency as a multiple of the maximum modulating frequency, f_m , i.e. $\Delta f = \beta f_m$.

Example: suppose in FM radio that the audio signal to be transmitted ranges from 20 to 15,000 Hz (it does). If the FM system used a maximum modulation index, β , of 5.0, then the frequency would "swing" by a maximum of $5 \times 15 \text{ kHz} = 75 \text{ kHz}$ above and below the carrier frequency.

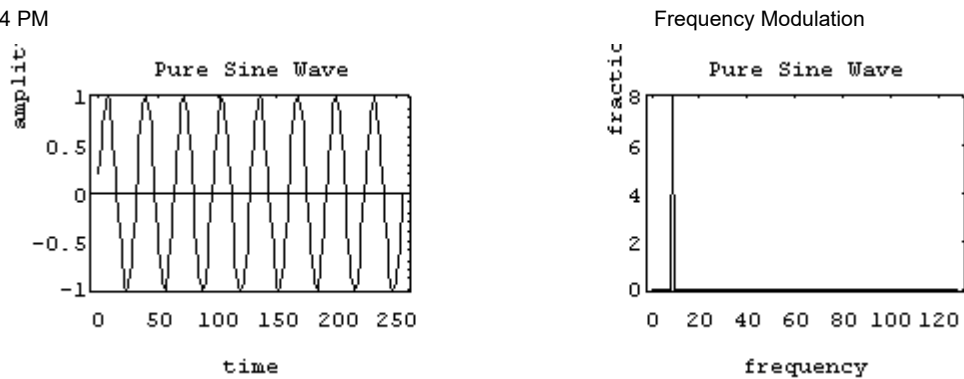
Here is a simple FM signal:



Here, the carrier is at 30 Hz, and the modulating frequency is 5 Hz. The modulation index is about 3, making the peak frequency deviation about 15 Hz. That means the frequency will vary somewhere between 15 and 45 Hz. How fast the cycle is completed is a function of the modulating frequency.

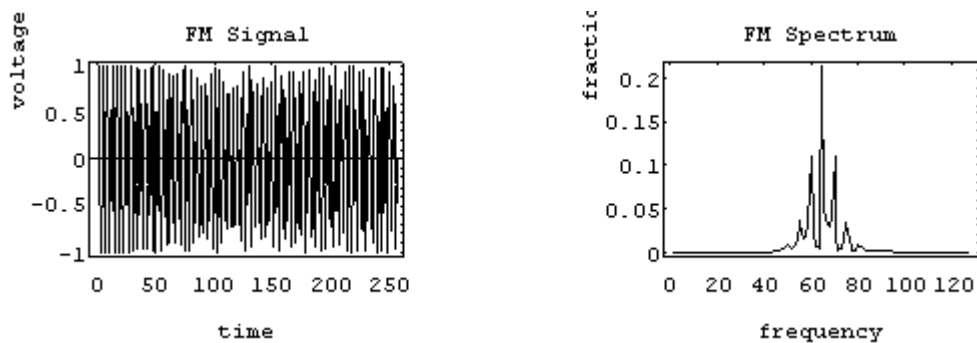
FM Spectrum

A spectrum represents the relative amounts of different frequency components in any signal. Its like the display on the graphic-equalizer in your stereo which has leds showing the relative amounts of bass, midrange and treble. These correspond directly to increasing frequencies (treble being the high frequency components). It is a well-know fact of mathematics, that any function (signal) can be decomposed into purely sinusoidal components (with a few pathological exceptions) . In technical terms, the sines and cosines form a complete set of functions, also known as a basis in the infinite-dimensional vector space of real-valued functions (gag reflex). Given that any signal can be thought to be made up of sinusoidal signals, the spectrum then represents the "recipe card" of how to make the signal from sinusoids. Like: 1 part of 50 Hz and 2 parts of 200 Hz. Pure sinusoids have the simplest spectrum of all, just one component:



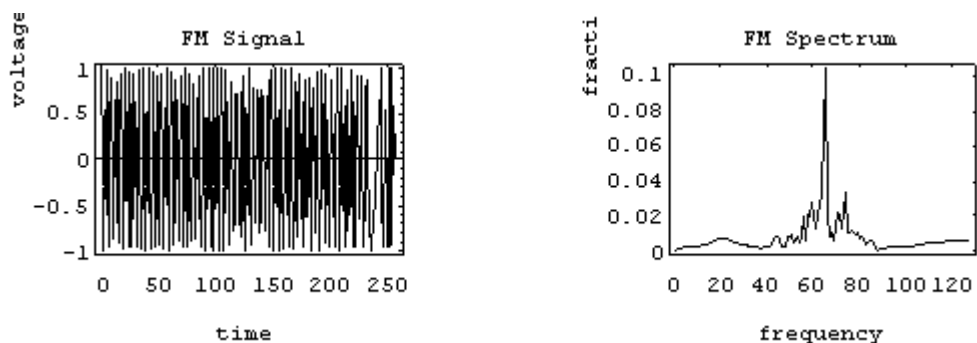
In this example, the carrier has 8 Hz and so the spectrum has a single component with value 1.0 at 8 Hz

The FM spectrum is considerably more complicated. The spectrum of a simple FM signal looks like:



The carrier is now 65 Hz, the modulating signal is a pure 5 Hz tone, and the modulation index is 2. What we see are multiple side-bands (spikes at other than the carrier frequency) separated by the modulating frequency, 5 Hz. There are roughly 3 side-bands on either side of the carrier. The shape of the spectrum may be explained using a simple heterodyne argument: when you mix the three frequencies (f_c , f_m and Δf) together you get the sum and difference frequencies. The largest combination is $f_c + f_m + \Delta f$, and the smallest is $f_c - f_m - \Delta f$. Since $\Delta f = \beta f_m$, the frequency varies $(\beta + 1) f_m$ above and below the carrier.

A more realistic example is to use an audio spectrum to provide the modulation:



In this example, the information signal varies between 1 and 11 Hz. The carrier is at 65 Hz and the modulation index is 2. The individual side-band spikes are replaced by a more-or-less continuous spectrum. However, the extent of the side-bands is limited (approximately) to $(\beta + 1) f_m$ above and below. Here, that would be 33 Hz above and below, making the bandwidth about 66 Hz. We see the side-bands extend from 35 to 90 Hz, so our observed bandwidth is 55 Hz.

You may have wondered why we ignored the smooth humps at the extreme ends of the spectrum. The truth is that they are in fact a by-product of frequency modulation (there is no random noise in this example). However,

they may be safely ignored because they have only a minute fraction of the total power. In practice, the random noise would obscure them anyway.

Example: FM Radio

FM radio uses frequency modulation, of course. The frequency band for FM radio is about 88 to 108 MHz. The information signal is music and voice which falls in the audio spectrum. The full audio spectrum ranges from 20 to 20,000 Hz, but FM radio limits the upper modulating frequency to 15 kHz (cf. AM radio which limits the upper frequency to 5 kHz). Although, some of the signal may be lost above 15 kHz, most people can't hear it anyway, so there is little loss of fidelity. FM radio may be appropriately referred to as "high-fidelity."

If FM transmitters use a maximum modulation index of about 5.0, so the resulting bandwidth is 180 kHz (roughly 0.2 MHz). The FCC assigns stations 0.2 MHz apart to prevent overlapping signals (coincidence? I think not!). If you were to fill up the FM band with stations, you could get $108 - 88 / .2 = 100$ stations, about the same number as AM radio (107). This sounds convincing, but is actually more complicated (agh!).

FM radio is broadcast in stereo, meaning two channels of information. In practice, they generate three signals prior to applying the modulation:

- the L + R (left + right) signal in the range of 50 to 15,000 Hz.
- a 19 kHz pilot carrier.
- the L-R signal centered on a 38 kHz pilot carrier (which is suppressed) that ranges from 23 to 53 kHz.

So, the information signal actually has a maximum modulating frequency of 53 kHz, requiring a reduction in the modulation index to about 1.0 to keep the total signal bandwidth about 200 kHz.

FM Performance

Bandwidth

As we have already shown, the bandwidth of a FM signal may be predicted using:

$$BW = 2 (\beta + 1) f_m$$

where β is the modulation index and

f_m is the maximum modulating frequency used.

FM radio has a significantly larger bandwidth than AM radio, but the FM radio band is also larger. The combination keeps the number of available channels about the same.

The bandwidth of an FM signal has a more complicated dependency than in the AM case (recall, the bandwidth of AM signals depend only on the maximum modulation frequency). In FM, both the modulation index and the modulating frequency affect the bandwidth. As the information is made stronger, the bandwidth also grows.

Efficiency

The efficiency of a signal is the power in the side-bands as a fraction of the total. In FM signals, because of the considerable side-bands produced, the efficiency is generally high. Recall that conventional AM is limited to about 33 % efficiency to prevent distortion in the receiver when the modulation index was greater than 1. FM has no analogous problem.

The side-band structure is fairly complicated, but it is safe to say that the efficiency is generally improved by making the modulation index larger (as it should be). But if you make the modulation index larger, so make the bandwidth larger (unlike AM) which has its disadvantages. As is typical in engineering, a compromise between efficiency and performance is struck. The modulation index is normally limited to a value between 1 and 5, depending on the application.

Noise

FM systems are far better at rejecting noise than AM systems. Noise generally is spread uniformly across the spectrum (the so-called white noise, meaning wide spectrum). The amplitude of the noise varies randomly at these frequencies. The change in amplitude can actually modulate the signal and be picked up in the AM system. As a result, AM systems are very sensitive to random noise. An example might be ignition system noise in your car. Special filters need to be installed to keep the interference out of your car radio.

FM systems are inherently immune to random noise. In order for the noise to interfere, it would have to modulate the frequency somehow. But the noise is distributed uniformly in frequency and varies mostly in amplitude. As a result, there is virtually no interference picked up in the FM receiver. FM is sometimes called "static free," referring to its superior immunity to random noise.

Summary

- In FM signals, the efficiency and bandwidth both depend on both the maximum modulating frequency and the modulation index.
- Compared to AM, the FM signal has a higher efficiency, a larger bandwidth and better immunity to noise.