Chapter 8: Frequency Modulation: Transmission

Chapter 8 Objectives

At the conclusion of this chapter, the reader will be able to:

- Explain how an oscillator is modulated to produce FM.
- Calculate the parameters of an FM signal, such as spectral content and bandwidth.
- Identify the topology of an FM transmitter.
- Predict the signals at each major point in an FM transmitter.
- Describe the technical characteristics of FM stereo multiplex and SCA signals.
- Explain how to use a station monitor to verify the operation of an FM transmitter.

In AM the voltage of the carrier signal is varied to represent the information. Because many noise sources produce amplitude disturbances, AM reception is very susceptible to them. Atmospheric noise (from lightning and other discharges) is a constant source of crackling and popping sounds in AM receivers.

Frequency modulation, or FM, was first theorized and experimented with in the 1930s. FM broadcasting on a large scale began in the late 1940s. In FM, the *frequency* of the carrier signal is changed to convey the information. The amplitude of the carrier remains constant.

There are two primary advantages to FM. First, since FM only changes the frequency, and not the amplitude of the carrier wave, FM receivers can be built to ignore amplitude (voltage) changes. Therefore, FM receivers ignore most external noise sources. Second, it is much easier to design systems to reproduce *high-fidelity* sound using FM. High-fidelity means accurate signal reproduction with a minimum of distortion. The reproduced information signal is a very close replica of the original in an FM system.

These advantages do come at a price. First, a typical FM broadcast station uses up to 200 kHz of bandwidth (compare this with the 10 kHz allotted for AM broadcast). Because of the high bandwidth requirements, FM broadcasting is done in the VHF band between 88 and 108 MHz and requires higher transmitter power. FM receivers and detectors are slightly more complex than those for AM, and the higher frequencies used for FM (VHF) complicate overall transmitter and receiver design.

For most serious music listeners, FM broadcast has become the medium of choice. AM broadcast has largely been relegated to talk radio, where high fidelity is not a serious concern.

Frequency and phase modulation (PM) are cousins. They are both considered *angle modulation*. PM directly changes the phase angle of the carrier wave to impart the information. FM indirectly changes the phase angle because it changes the frequency (which is the rate of phase change). PM is rarely broadcast directly for voice communications, but instead is used to gain an analytical understanding of FM. PM does find heavy application in digital (data) communications, the subject of a later chapter.

8-1 A Simple FM Transmitter

To create frequency modulation, the frequency of the carrier signal must be changed in step with the information signal. This suggests that the modulation process should take place at the *oscillator*. An RF oscillator's frequency can be controlled by using an LC resonant circuit, so if we can make either the L or C change in step with the information, frequency modulation will be created. Figure 8-1 shows one way of doing this. It's not an entirely practical way of building an FM transmitter, but it works!

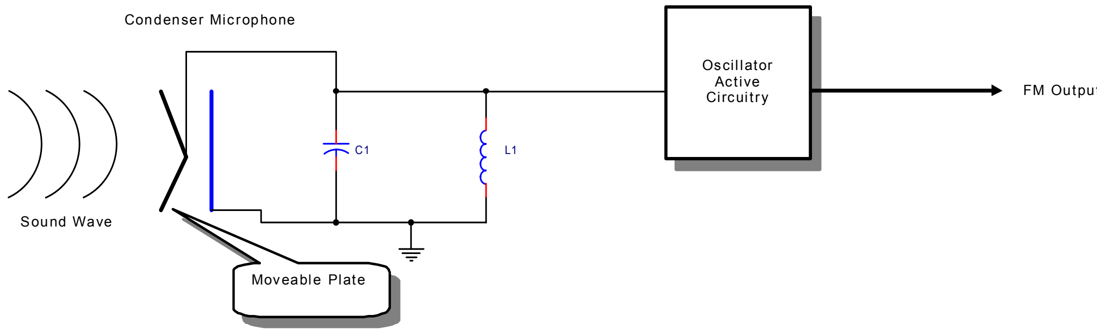

Figure 8-1: A Crude FM Transmitter

The circuit in Figure 8-1 has a unique type of microphone connected in parallel with the LC resonant tank circuit of the oscillator. This is a *condenser* or *capacitance* microphone. The condenser mike has two metal plates separated by an insulating air space. One of the plates is very thin (like a piece of aluminum foil) and is free to vibrate back and forth when sound strikes it. When sound strikes the moveable plate of the condensor microphone, it causes the capacitance of the microphone to change in step with the sound. Recall that the capacitance of a capacitor is given by

(8-1) $$C = \frac{\varepsilon A}{d}$$

Where ε is the *dielectric constant* of the insulating material (air in this case), A is the area of one of the capacitor plates, and d is the distance between the plates.

The vibration of the capacitance microphone's plate causes the distance between the plates to vary in step with the information. Thus, the total tank capacitance varies in step with the information. Varying the tank capacitance changes the resonant frequency, which in turn changes the oscillator frequency.

In other words, the condenser microphone *frequency modulates* the oscillator circuit. When the microphone plates are closer together, the total tank capacitance increases, causing the resonant frequency to *decrease*. The opposite happens when the plates move farther apart; the total tank capacitance decreases, causing the oscillator to *increase* in frequency. Since it is the information (sound) that is causing the condenser microphone's moveable plate to vibrate, the frequency changes on the carrier will follow the information signal. Figure 8-2 shows this relationship.

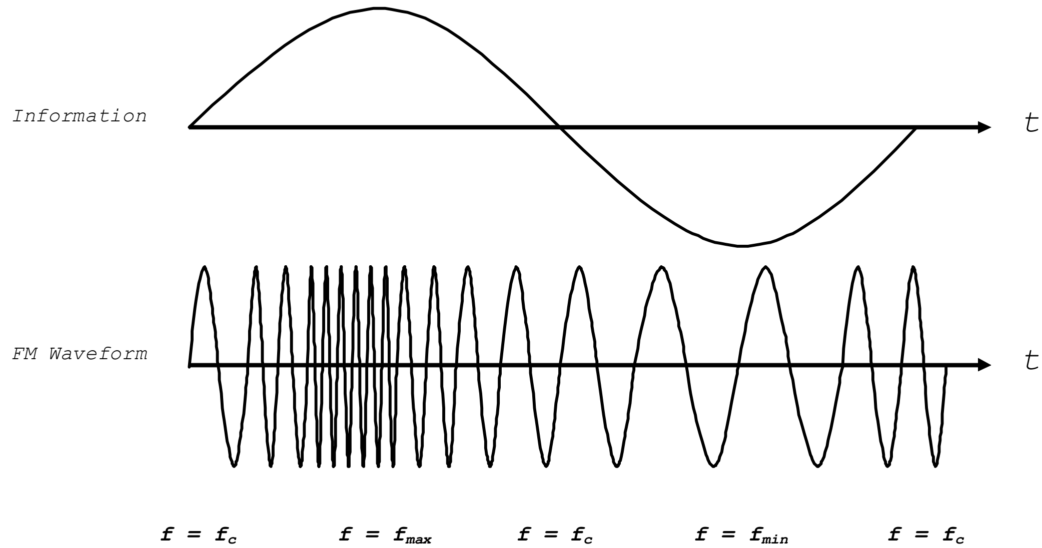

Figure 8-2: The Information Signal and the Resulting FM Carrier Waveform

The FM carrier waveform in Figure 8-2 has a *constant* amplitude. The only thing that changes is the *frequency*. When the information signal is positive, the FM signal's frequency increases. The cycles of the carrier waveform are squeezed closer together here. On the negative half-cycle, the opposite happens -- we can see the carrier waveform spreading out. Its period has lengthened, indicating a lower frequency.

The capacitor microphone isn't a very practical method of generating FM. Because its wire leads are part of the tank circuit, moving the microphone would cause the capacitance of the tank circuit to shift, forcing the transmitter off frequency! In an actual FM transmitter, we use an electronic circuit called a *reactance modulator* to replace the condenser microphone. A reactance modulator converts a changing voltage into a changing capacitance (or inductance). This eliminates the need for the condenser microphone, and allows an intelligence voltage to modulate the transmitter. Reactance modulators will be presented in a later section.

Center Frequency and Deviation

In Figure 8-2, the FM waveform is changing frequency in step with the information signal. Whenever the information signal is passing through zero, the frequency of the waveform is equal to the *carrier frequency* of the transmitter.

The frequency produced by an FM transmitter when no information voltage is present is known by many names. Among these are the *carrier* frequency, the *center* frequency, and the *resting* frequency.

When the information signal goes to its maximum positive value, the instantaneous carrier frequency also becomes maximum. This is indicated by f_{max} in Figure 8-2. Likewise, the minimum frequency produced, f_{min}, occurs at the negative peak of the information signal.

The *deviation* of an FM transmitter is equal to the *peak* frequency change produced by the information signal. The symbol δ (the lowercase Greek letter *delta*) is often used to represent the deviation. We can calculate the deviation in two ways:

(8-2) $\delta = f_{\max} - f_c$

(8-3) $\delta = f_c - f_{\min}$

Both equations will give the same result. The carrier frequency normally swings equally above and below the center frequency. The deviation plays a major role in determining the *bandwidth* of an FM transmitter, so it is very useful to calculate it.

What controls the amount of deviation? Since deviation is just frequency change, we can see that the *voltage* or *amplitude* of the information must be responsible. Again, look at Figure 8-2. As the information voltage increases, the frequency increases. If the information voltage were made larger, the amount of frequency change (deviation) would increase in direct proportion. The deviation will decrease if the information voltage is made smaller. Since the voltage of the information is related to its loudness, we can say that increasing the volume of the sound at the transmitter will increase the amount of deviation produced.

The quantity of deviation is *directly proportional* to the amplitude of the information. Doubling the information voltage will double the deviation; halving the information voltage cuts the deviation in half.

Example 8-1

Suppose that the center frequency f_c in Figure 8-2 is 100 kHz, and that f_{min} = 95 kHz, and f_{max} = 105 kHz. The information signal Vm is 5 V peak.

a) Calculate the deviation, δ
b) Recalculate the deviation if the information signal is increased to 7.5 V peak.

Solution
Since we know both f_{max} and f_{min}, we can use either Equation 8-2 or 8-3. Substituting, we get:

$$\delta = f_{\max} - f_c = 105kHz - 100kHz = \underline{\underline{5\ kHz}}$$

The deviation is *directly proportional* to the information voltage. We can set up a proportion as follows:

$$\frac{Vm'}{Vm} = \frac{\delta'}{\delta}$$

Don't let this scare you! We're just saying that the *new* information voltage, *Vm'* (the ' mark is pronounced "prime" and means "new value") compared to the *old* information voltage, *Vm*, will be the same as the *new* deviation compared to the *old*.

We know *Vm* and *Vm'*, and the original deviation. A little rearranging will give us:

$$\delta' = \delta\left(\frac{Vm'}{Vm}\right) = 5\ kHz\left(\frac{7.5V}{5V}\right) = \underline{\underline{7.5\ kHz}}$$

The new deviation will increase to 7.5 kHz. This will also increase the amount of frequency space, or *bandwidth* required by the FM signal. This will be one of the topics of the next section.

Section Checkpoint

8-1 Why are FM receivers largely unbothered by static?
8-2 List two advantages of FM compared to AM.
8-3 Why does an FM broadcast transmitter require more power to provide the same coverage as an AM broadcast transmitter?
8-4 What frequency range is used for FM broadcast and why?
8-5 List the two forms of *angle modulation.*
8-6 Where is the modulation performed in an FM transmitter?
8-7 How can a capacitor microphone help in generating FM?
8-8 How could the amplitude of an FM signal be described?
8-9 What does a *reactance modulator* do?
8-10 What are two other names for the *center frequency* of an FM transmitter?
8-11 Explain how to calculate *deviation* for an FM transmitter.
8-12 What controls the amount of deviation in an FM transmitter?

8-2 FM Signal Analysis

During the analysis of AM in Chapter 3, we looked at AM signals in both the time and frequency domains. An FM signal can be examined in the same ways. One thing we quickly discover is that an FM signal doesn't look very impressive on an oscilloscope! The frequency changes (deviation) shown in Figure 8-2 are greatly exaggerated. *You will rarely be able to directly observe the frequency deviation of an FM signal on an oscilloscope*. The amount of frequency change is fairly small when compared to the carrier center frequency. A "real life" FM signal is shown in Figure 8-3:

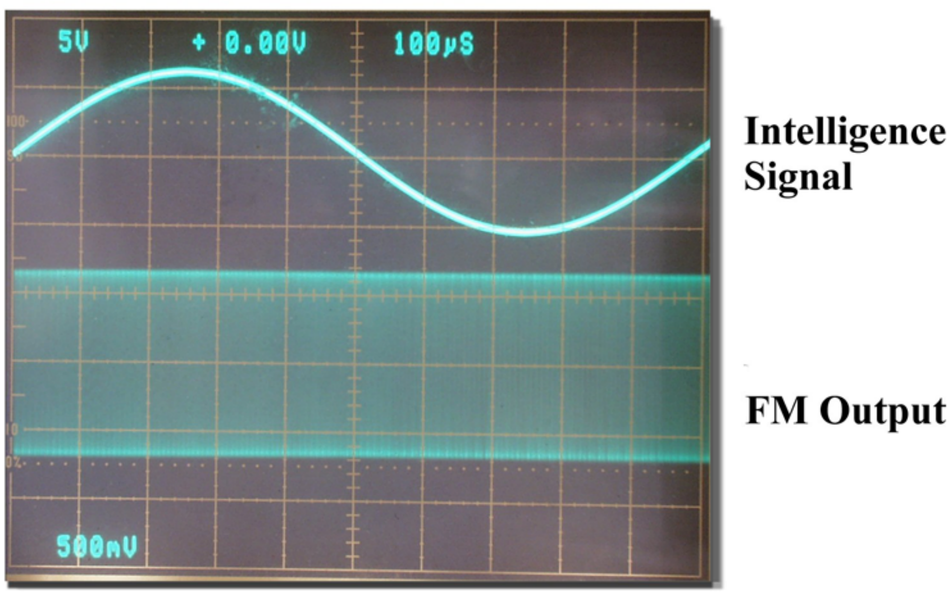

Figure 8-3: An FM signal On an Oscilloscope (f_c = 100 kHz, δ=5 kHz)

As you might have guessed, we'll receive a lot more information by looking at an FM signal in the frequency domain with a spectrum analyzer. There are four specific quantities that a technician normally can be expected to measure or estimate in an FM signal. These are the *percentage of modulation,* the *deviation rate*, the *modulation index*, and the *bandwidth*.

Percentage of Modulation

In AM, the percentage of modulation is a practical measure of how much information voltage is being placed on top of the carrier. The more information voltage, the louder the sound in the receiver. The definition holds the same practical meaning for FM, but the formula for calculating it is different. For FM, percentage of modulation is defined by

$$\text{(8-4)} \quad \%MOD = \left(\frac{\delta}{\delta_{\max}}\right) \times 100\%$$

In Equation 8-4, δ is the deviation of the transmitter, and δ_{max} is the maximum allowed deviation for the particular type of FM transmission being used. For broadcast FM, δ_{max} is 75 kHz. For the sound portion of an analog TV signal, an FM carrier is used, with a δ_{max} of 25 kHz. Communications FM (such as emergency services and amateur radio) commonly uses a δ_{max} of 5 kHz. *To calculate FM percentage of modulation, you must know the maximum allowed deviation!*

You might wonder why "communications" applications use such a small amount of deviation when compared to FM broadcast. High-fidelity isn't a strong design goal for voice communications. Instead, a large number of users must share a fixed amount of RF spectrum (frequency space). By lowering deviation, the bandwidth required for each transmitter is reduced -- and therefore, more transmitters can share the airwaves.

Example 8-2

An FM broadcaster is operating on 98.1 MHz, and the maximum frequency from the transmitter is 98.15 MHz. The information voltage is 5 Vpk, and the information frequency is 1 kHz.
a) What is the percentage of modulation?
b) If the information voltage is changed to 4 Vpk, what happens to the percentage of modulation?
c) What information voltage will 100% modulate the transmitter?

Solution
a) To calculate percentage of modulation, we must first know deviation:

$$\delta = f_{\max} - f_c = 98.15MHz - 98.1MHz = \underline{50\ kHz}$$

Since this is an FM broadcast (88 - 108 MHz), we know that the maximum deviation is 75 kHz. Therefore:

$$\%MOD = \left(\frac{\delta}{\delta_{\max}}\right) \times 100\% = \left(\frac{50kHz}{75kHz}\right) \times 100\% = \underline{\underline{66.7\%}}$$

b) The information voltage controls the deviation. Since the voltage has *decreased* to 4 Vpk, we can expect the amount of deviation to decrease in a like manner:

$$\delta' = \delta\left(\frac{Vm'}{Vm}\right) = 50\ kHz\left(\frac{4Vpk}{5Vpk}\right) = \underline{40\ kHz}$$

This isn't exactly the answer that was needed; we need to express it as a percentage of modulation:

$$\%MOD = \left(\frac{\delta}{\delta_{\max}}\right)\times 100\% = \left(\frac{40kHz}{75kHz}\right)\times 100\% = \underline{\underline{53.3\%}}$$

c) This is a rather "backwards" request, but it is quite solvable. Remember that 100% modulation is 75 kHz (the deviation we desire), and substitute that into the proportion for deviation:

$$\frac{Vm'}{Vm} = \frac{\delta'}{\delta}$$

Here Vm' is the new (unknown) information voltage, δ' is the new (desired) deviation, and Vm and δ are the original values. By manipulating the equation, we get:

$$Vm' = \left(\frac{\delta'}{\delta}\right)Vm = \left(\frac{75kHz}{50kHz}\right)5Vp = \underline{\underline{7.5\ Vpk}}$$

Therefore, an information voltage of 7.5 Vpk will be required to 100% modulate the transmitter.

Deviation Rate

The *deviation rate* (DR) of an FM transmitter is the number of up and down frequency changes (swings) of the RF carrier that take place per second. It is always the same as the *information frequency*.

Suppose that we send a very low information frequency, 1 Hz into an FM modulator. The carrier will swing up to its maximum frequency, down to its minimum frequency, then back to center again exactly *once* every second.

If the information is increased to 2 Hz, then the carrier frequency changes will take place *twice* per second. It doesn't matter what the information voltage is. Only the *frequency* of the information is important in determining deviation rate.

Example 8-3

An FM broadcaster is operating on 96.5 MHz, and the maximum frequency from the transmitter is 96.54 MHz. The information voltage is 5 Vpk, and the information frequency is 1 kHz.
a) What is the deviation rate (DR)?
b) If the information voltage is changed to 2 Vpk, what happens to the deviation rate?
c) If the information frequency is changed to 5 kHz, what happens to the deviation rate?

Solution
a) DR = f_m = 1 kHz by inspection.

b) The DR is unchanged; it is still 1 kHz, since only the information frequency affects it.

c) The DR becomes the new f_m value or 5 kHz by inspection.
Only the frequency of the information affects the deviation rate!

FM Modulation Index

Another measure of FM transmitter performance is the *modulation index*, usually denoted by the symbol m_f. It's easy to become confused here, because the meaning of modulation index is quite different for FM than it was for AM.

Recall that for AM, modulation index and percentage of modulation are essentially the same information. The AM modulation percentage is merely the AM modulation index (a number between zero and one) expressed as a percentage.

In FM, percent modulation and modulation index are *not* the same information! The FM modulation index is a measure of how much *phase shift* is being imparted to the carrier wave by the information. "Now wait," you say. "In FM, the *frequency* of the carrier is being changed. How are we getting a phase shift?"

Any time we change the frequency of a waveform, we create the same effect as an increasing phase shift. For FM, the peak or maximal amount of this phase shift is calculated by

(8-5) $$m_f = \frac{\delta}{f_m}$$

where δ is the deviation (Hz), f_m is the information frequency (Hz), and m_f is the *FM modulation index, in radians*. Don't let this bother you. Remember that there are 2π radians in a circle, or 360 degrees. If there is an FM modulation index of π, then the maximum carrier phase shift is simply 180°.

The relationship between phase shift and frequency can be visualized by looking at the second hand on a wall clock. In Figure 8-4(a), the body of the clock is stationary and the second hand completes a revolution once every minute. But what if the clock is rotated *clockwise* at the same time (Figure 8-4(b))? To the observer, the second hand appears to move *faster*. The eye sees that the "frequency" of the second hand has increased.

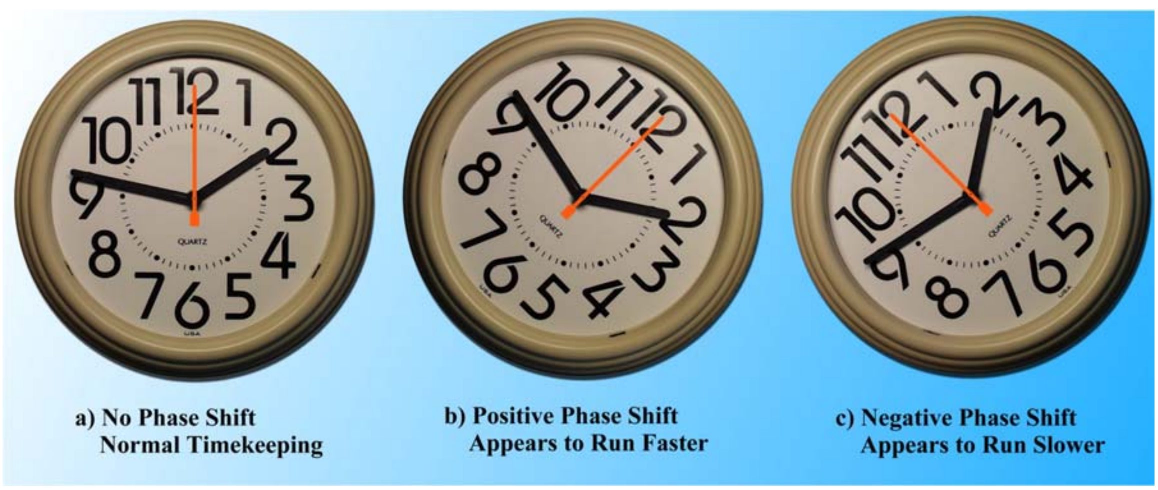

Figure 8-4: Clock Watching

In Figure 8-4(c), the clock now appears to be running *slower*; something is rotating the clock *counter clockwise*.

The maximum *angle* that the clock is rotated through is analogous to the FM modulation index. Here's the catch: Suppose that all you can see is the second hand. You can't see the clock face, or case. You notice the second hand speeding up (frequency increasing). Is the second hand speeding up on its own, or is the clock being turned ("phase shifted")? You have no way of knowing for sure!

When a phase shift is taking place on a carrier wave, it causes the apparent frequency of the carrier wave to either increase (positive phase shift) or decrease (negative phase shift). For this to happen, the phase shift must be changing (not a constant value). Stop turning the clock, but leave it at any angle, and the second hand again moves at its normal speed. Likewise, increasing the frequency of a carrier wave has same effect as an *equivalent amount of increasing phase shift*.

That's the rub -- frequency modulating the carrier wave actually creates PM, and the *modulation index* is really the *amount* of PM being generated. Likewise, you can look at it the other way-- if we phase modulate a carrier, it will also appear that we've *frequency modulated* it. PM and FM are different types of modulation, but you can't have one without the other!

The FM modulation index m_f is a good measure of how strongly we're modulating the carrier. It will also be very helpful in calculating the bandwidth of the FM signal. Equation 8-5 tells us that the FM modulation index depends on two factors, the *deviation* (which is controlled by the amplitude of the information), and the *information frequency* or *deviation rate*.

Example 8-4

An FM broadcaster is operating on a carrier frequency 93.3 MHz, and with a 1 Vpk information signal, the transmitter is producing 10 kHz of deviation. The carrier is swinging up and down in frequency 5,000 times per second. Calculate:
a) The information frequency f_m
b) The deviation rate (DR)
c) The percentage of modulation
d) The FM modulation index

Solution
a) The carrier frequency swing rate is equal to the information frequency. By inspection, $\underline{\underline{f_m = 5\ kHz}}$.

b) The deviation rate (DR) is equal to the information frequency, and is also $\underline{\underline{5\text{ kHz}}}$.

c) The percentage of modulation is:

$$\%MOD = \left(\frac{\delta}{\delta_{\max}}\right)\times 100\% = \left(\frac{10kHz}{75kHz}\right)\times 100\% = \underline{\underline{13.3\%}}$$

d) The FM modulation index is:

$$m_f = \frac{\delta}{f_m} = \frac{10kHz}{5kHz} = \underline{\underline{2.0\ radians}}$$

There is no "theoretical maximum" for modulation index, but most broadcasting keeps m_f at or below 15.

Changes in the information frequency or information voltage will alter the FM modulation index. Equation 8-5 tells us that as we increase the frequency of the information, the FM modulation index will fall (all else being constant). If we increase the amplitude of the intelligence, (which increases deviation), the modulation index will rise in a like manner.

FM Bandwidth Analysis

AM and FM signals appear quite different in the frequency domain. You might recall that an AM signal generates one pair of sidebands for each information tone frequency being applied to the transmitter. For example, a spectrogram of a 100 kHz 10 volt carrier being 100% amplitude modulated by a 5 kHz tone would look like Figure 8-5.

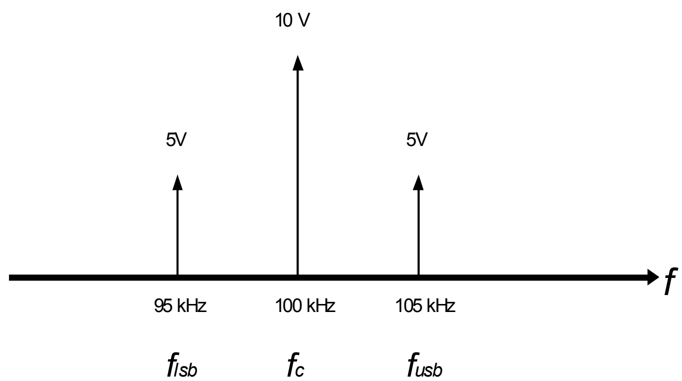

Figure 8-5: The Spectrogram of an AM Signal

An FM signal looks quite different. If we frequency-modulate a 100 kHz carrier with a 5 kHz information signal, we get a picture like Figure 8-6.

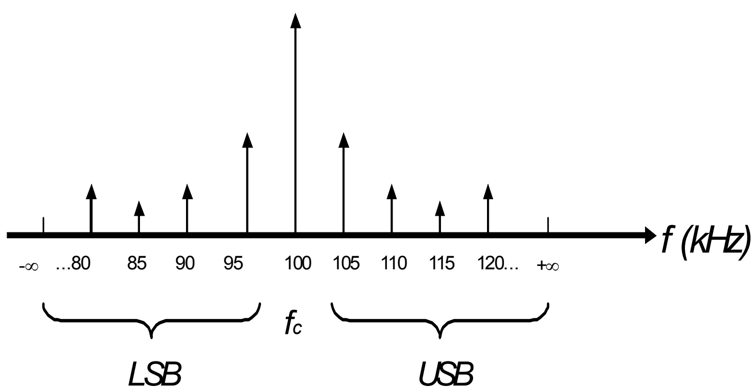

Figure 8-6: The Spectrogram of an FM Signal

There's something really strange about Figure 8-6. Count the number of sidebands being generated: They go from a frequency of $-\infty$ to $+\infty$, stepping 5 kHz (f_m) as they go. In other words, *in theory, any FM signal always has an infinite number of sidebands, and requires an infinite bandwidth to represent.* In practice, you might guess that we don't have to worry about *all* of the sidebands of an FM signal, and you're right. Notice that as we get far away from the carrier, the sidebands tend to get weaker. Eventually, they dip below the noise level -- at which point they become insignificant.

An exact calculation of the bandwidth of an FM signal is a little involved, and for that reason, we often use an approximation called *Carson's Rule:*

Carson's Rule (8-6) $BW \approx 2(f_m + \delta)$

Carson's rule is a nice quick way of finding bandwidth. It has two "parts" which make sense when Equation 8-6 is unfactored (distributed). The first part, $2f_m$, looks a lot like the equation for the bandwidth of an AM signal. This part is true because any FM signal produces *at least* two significant sidebands. The other part of Carson's rule is the intuitive part. If you cause a transmitter to deviate 5 kHz up, and 5 kHz down (δ=5 kHz), you would naturally expect the FM transmitter to use up two times 5 kHz, or 10 kHz of bandwidth. You might wonder why we don't just go with this part of the rule and be done; it looks simple enough. Unfortunately, FM is a *nonlinear* form of modulation. Many of the aspects of the behavior of FM defy intuition because of this. We will compare the intuitive and actual results of FM signal analysis shortly.

Example 8-5

An FM broadcaster is operating on a carrier frequency 93.3 MHz, and with a 1 V_{pk} information signal, the transmitter is producing 10 kHz of deviation. The information frequency is 5 kHz. Calculate the bandwidth by Carson's rule, and compare it with the "intuitive" result (twice deviation.)

Solution
Carson's rule states that:

$$BW \approx 2(f_m + \delta) \approx 2(5KHz + 10KHz) \approx \underline{\underline{30KHz}}$$

Approximately 30 kHz of bandwidth will be needed by the transmitter.

The intuitive approach (which gives a wrong answer) says that the transmitter frequency is swinging *up* 10 kHz and then *down* 10 kHz, for a total "frequency travel" of 20 kHz. Unfortunately, this approach just isn't very accurate, though. The reason is that FM generates an infinite number of sidebands, and there is nothing in this approach to account for that -- which ones will be significant, and which ones can be ignored? The two terms in Carson's rule take into account an *approximate* count of the number of significant sidebands.

Exact Bandwidth of an FM Signal

In order to get an accurate estimate of the bandwidth of an FM signal, we must use an equation known as *Bessel's Identity*. The formula is too complex to explore here, but the results are quite valuable. Bessel's identity gives the relative voltage of the carrier and each sideband in an FM signal *compared to the original unmodulated carrier voltage*. The numbers in the Bessel chart, then, are really just percentages.

The *FM modulation index* must first be calculated in order to look up results in a Bessel table. In a Bessel table, the symbol J_0 stands for the *carrier*, J_1 for the first pair of sidebands, J_2 for the second pair of sidebands, and so on. Table 8-1 shows a Bessel table covering modulation indices from 0 to 15.

Bessel Functions of Order N

m_f	J0	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16
0.00	1.000																
0.20	0.990	0.100															
0.25	0.984	0.124															
0.50	0.938	0.242	0.031														
1.00	0.765	0.440	0.115	0.020													
1.50	0.512	0.558	0.232	0.061	0.012												
2.00	0.224	0.577	0.353	0.129	0.034												
2.41	0.000	0.519	0.432	0.199	0.065	0.016											
2.50	-0.048	0.497	0.446	0.217	0.074	0.020											
3.00	-0.260	0.339	0.486	0.309	0.132	0.043	0.011										
4.00	-0.397	-0.066	0.364	0.430	0.281	0.132	0.049	0.015									
5.00	-0.178	-0.328	0.047	0.365	0.391	0.261	0.131	0.053	0.018								
5.52	0.000	-0.340	-0.123	0.251	0.396	0.323	0.189	0.088	0.034	0.012							
6.00	0.151	-0.277	-0.243	0.115	0.358	0.362	0.246	0.130	0.057	0.021							
7.00	0.300	-0.005	-0.301	-0.168	0.158	0.348	0.339	0.234	0.128	0.059	0.024						
8.00	0.172	0.235	-0.113	-0.291	-0.105	0.186	0.338	0.321	0.223	0.126	0.061	0.026	0.010				
9.00	-0.090	0.245	0.145	-0.181	-0.265	-0.055	0.204	0.327	0.305	0.215	0.125	0.062	0.027	0.011			
10.00	-0.246	0.043	0.255	0.058	-0.220	-0.234	-0.014	0.217	0.318	0.292	0.207	0.123	0.063	0.029	0.012		
12.00	0.048	-0.223	-0.085	0.195	0.182	-0.073	-0.244	-0.170	0.045	0.230	0.300	0.270	0.195	0.120	0.065	0.032	0.014
15.00	-0.012	0.206	0.042	-0.194	-0.119	0.130	0.206	0.034	-0.174	-0.220	-0.090	0.100	0.237	0.279	0.246	0.181	0.116

Table 8-1: Bessel Coefficients for m_f Between 0 and 15.

To use the Bessel table, we first calculate the FM modulation index, m_f. Then we look down the first column of the table until we find a matching m_f value. The numbers on the same line as this value represent the *normalized voltages* in the carrier (J_0), first pair of sidebands (J_1), second pair of sidebands (J_2), and so forth.

The table does not show any values that are less than 1% (0.01) of the original carrier's voltage. *A "significant" sideband is one that will be counted when tallying the bandwidth, and must have at least 1% of the original unmodulated carrier amplitude.* Technically, these sidebands are no weaker than -40 dBc (decibels with respect to the unmodulated carrier).

Take a look at the figures across the top row of Table 8-1, where m_f is 0. The value J_0 reads as 1.000 (100%), and all the other columns show blanks (J_1 - J_{16}). When the modulation index is zero, we have an *unmodulated carrier*, which is just a steady sine wave. With no modulation taking place, there are no sidebands, and therefore the carrier (J_0) is 100% of its original value.

Example 8-6

Use a Bessel table to evaluate the FM transmitter from Example 8-5, and plot a spectrogram of the resulting FM signal. V_c*(unmodulated)* = 100 volts, and R_L = 50 ohms.

Solution
The data from Example 8-5 are: f_c = 93.3 MHz, δ = 10 kHz, and f_m = 5 kHz.

To use a Bessel table, we must first find the FM modulation index:

$$m_f = \frac{\delta}{f_m} = \frac{10KHz}{5KHz} = \underline{2.0}$$

From the Bessel table, we read the Figures from the *2.0* row and get:

J_0 = 0.224, J_1 = 0.577, J_2 = 0.353, J_3 = 0.129, and J_4 = 0.034. The remaining figures in the row are blank, indicating that the rest of the sideband voltages (J_5 - J_{16}) are less than 1% of the unmodulated carrier value, and are therefore insignificant.

We can now calculate the voltage of each spectral component:

$$V_c = J_0 V_{c(un\,\mathrm{mod})} = (0.224)(100V) = \underline{\underline{22.4V}}$$
$$V_{LSB[1]} = V_{USB[1]} = J_1 V_{c(un\,\mathrm{mod})} = (0.577)(100V) = \underline{\underline{57.7V}}$$
$$V_{LSB[2]} = V_{USB[2]} = J_2 V_{c(un\,\mathrm{mod})} = (0.353)(100V) = \underline{\underline{35.3V}}$$
$$V_{LSB[3]} = V_{USB[3]} = J_3 V_{c(un\,\mathrm{mod})} = (0.129)(100V) = \underline{\underline{12.9V}}$$
$$V_{LSB[4]} = V_{USB[4]} = J_4 V_{c(un\,\mathrm{mod})} = (0.034)(100V) = \underline{\underline{3.4V}}$$

The *frequency* of each sideband is equal to the carrier plus a multiple of the original information frequency. The resulting spectrogram is shown in Figure 8-7.

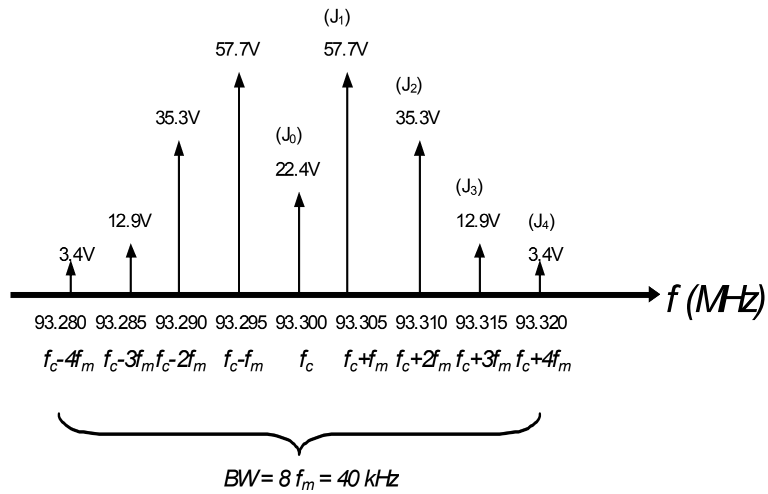

Figure 8-7: The Resulting FM Signal Spectrogram

The total bandwidth of the emission is $8f_m$, because there are four sideband *pairs*, with a frequency space of f_m between them. This is a 40 kHz bandwidth, moderately wider than the 30 kHz bandwidth estimated by Carson's rule for the same data.

Note how we do *not* divide the Bessel coefficients for the sidebands by two. That has already been accounted for in the Bessel table.

The Total Power Remains Constant

As we increase the modulation index, something interesting happens to the carrier energy. The power in an FM signal must remain constant. But how can the total power remain constant if we're adding *sidebands* as we modulate the carrier? The Bessel table gives the answer. The *carrier* (J_0) shrinks as the sidebands grow. In essence, the sidebands "steal" power from the carrier. This way, the total power can remain constant. Figure 8-8 shows this in graphic form.

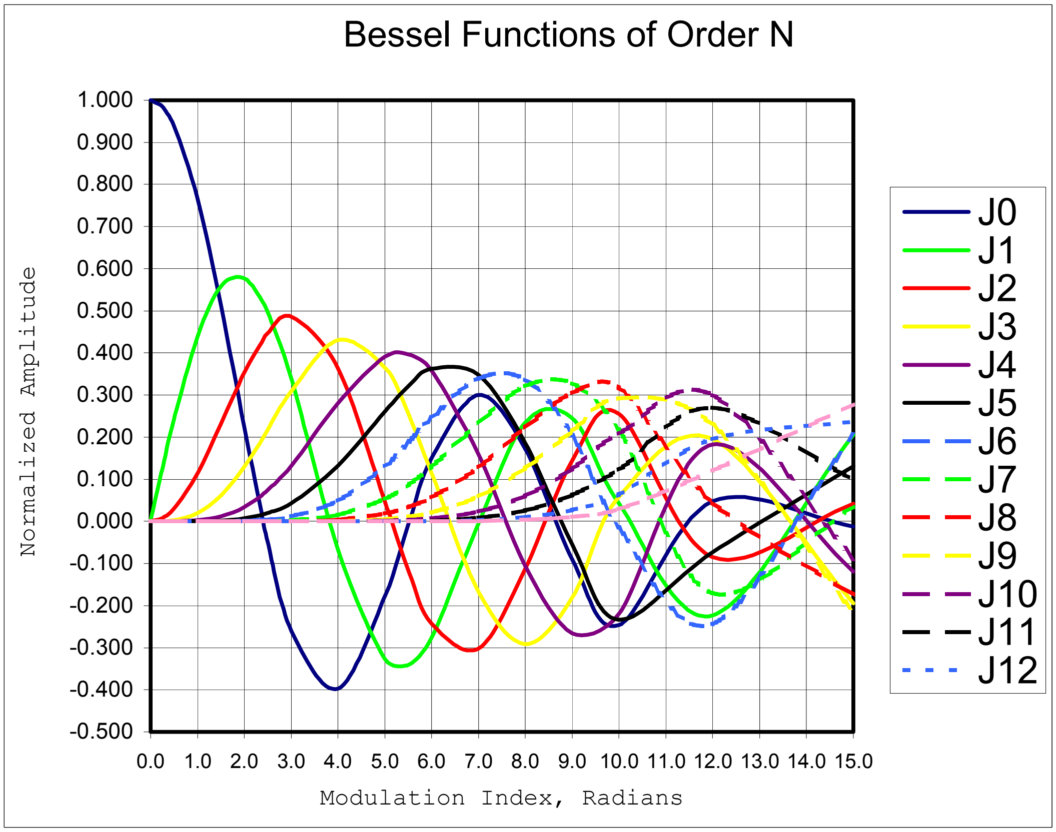

Figure 8-8: The Graph of the Bessel Functions

Figure 8-8 contains the same information as the Bessel table. The horizontal axis of the graph is the modulation index. The left-hand side of the graph is a modulation index of *zero*, which means an unmodulated FM carrier. Which frequency components are present when $m_f = 0$? Only the carrier, since the dark blue line representing J_0, the carrier frequency component, is at *1.00*, while all the other graph lines are at zero. As the FM modulation index is increased, you can see the carrier strength weaken as more sidebands are added. On a spectrum analyzer, the expanding pattern of sidebands looks like "grass growing" as the modulation index is increased.

Example 8-7

Calculate the power of the transmitter in Example 8-6 when unmodulated (m_f =0), and when modulated according to the conditions in the previous example. Show the power of each signal component on a spectrogram, and find the total power.

Solution

When the transmitter is unmodulated the only signal energy is the 100 volt carrier. Under this condition, the total power will be:

$$P = \frac{V_{c(un\,\mathrm{mod})}^2}{R_L} = \frac{100V^2}{50\Omega} = \underline{\underline{200W}}$$

When the transmitter is modulated, we need to find the power in each individual frequency component by using Ohm's law, just like above. For example, when modulated, the new carrier power will be:

$$P_c = \frac{V_c^2}{R_L} = \frac{\left(J_0 V_{c(un\,\mathrm{mod})}\right)^2}{R_L} = \frac{22.4\ V^2}{50\Omega} = \underline{\underline{10.04\ W}}$$

This process is repeated for all the frequencies in Figure 8-7, yielding the spectrogram of Figure 8-9.

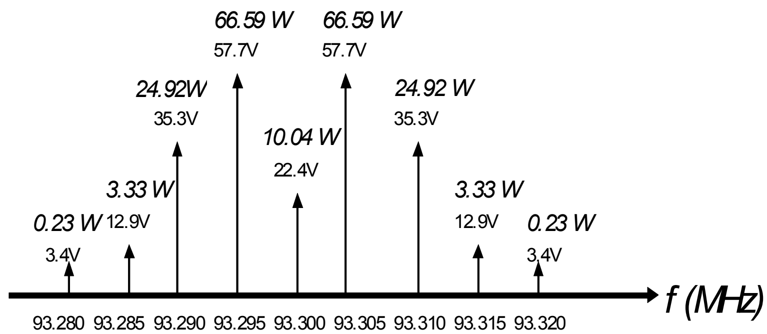

Figure 8-9: The Spectrogram with Power

The total power is therefore (2)(0.23W) + (2)(3.33W) + (2)(24.92W) + (2)(66.59W) + 10.04 W = 200.18 W. This is very close to the original value of 200 W; the extra 0.18 W is due to rounding errors inherent in the Bessel table.

Special Cases for FM Transmission

There are two types of FM signals that most technicians can recognize on a spectrum analyzer, *wideband* and *narrowband* FM. The preceding example is a *wideband* FM (WBFM) signal. It has more than one pair of significant sidebands. *Whenever the FM modulation index is greater than 0.25, a wideband FM signal will result*. The Bessel table verifies this; the largest index m_f where there is only one pair of sidebands (J_2 and higher are zero) is *0.25*.

Any FM signal that has only *one* pair of significant sidebands is called a *narrowband* FM (NBFM) signal. *The modulation index of a NBFM signal is always less than or equal to 0.25.*

It's easy to calculate the bandwidth of a NBFM signal; just multiply the information frequency by two! The reason for this again comes from the Bessel table. In a NBFM signal, there is only one pair of significant sidebands, with a voltage given by coefficient J_1. Since the sidebands are spaced at intervals of f_m, the bandwidth becomes $2f_m$.

Example 8-8

An FM transmitter is using a carrier frequency of 100 kHz, and has a deviation of 1 kHz, and an information frequency of 4 kHz. The unmodulated carrier voltage is 10 V. Draw a spectrogram, and decide whether this is a NBFM or WBFM signal.

Solution
First, calculate the modulation index: