Operational Diagrams
of
Radio Transmitters & Receivers

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<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>4 - 5</td>
</tr>
<tr>
<td>Introduction</td>
<td>6 - 7</td>
</tr>
<tr>
<td>Operation of Adder-Antenna Transmitter</td>
<td>9</td>
</tr>
<tr>
<td>Operation of AM Transmitter in General</td>
<td>10</td>
</tr>
<tr>
<td>Operation of AM Transmitter Showing AM Modulator in Detail</td>
<td>11</td>
</tr>
<tr>
<td>Operation of TRF AM Receiver</td>
<td>12</td>
</tr>
<tr>
<td>Operation of Superheterodyne AM Receiver</td>
<td>13</td>
</tr>
<tr>
<td>Operation of PM Transmitter</td>
<td>14</td>
</tr>
<tr>
<td>Operation of FM Transmitter in General</td>
<td>15</td>
</tr>
<tr>
<td>Operation of FM Transmitter with Indirect Modulation</td>
<td>16</td>
</tr>
<tr>
<td>Operation of FM Transmitter with Direct Modulation</td>
<td>17</td>
</tr>
<tr>
<td>Operation of FM Receiver</td>
<td>18 - 19</td>
</tr>
<tr>
<td>Operation of PM Receiver</td>
<td>20</td>
</tr>
<tr>
<td>Conclusion</td>
<td>21</td>
</tr>
</tbody>
</table>
PREFACE

The purpose of these diagrams is to graphically explain the overall operation of AM, PM, and FM communications systems using very little mathematics. This explanation is accomplished by tracing a simple sinusoidal signal through all stages of each system. Although students who are "mathematically challenged" will find these diagrams very helpful, most students who are beginning the study of electrical communications systems can benefit from these same diagrams. More advanced courses can also use these diagrams as a basis on which to organize and present abstract mathematics.

The unique features of these diagrams are the following:

- Presenting the signal in both the time domain and frequency domain together at each stage of the communication process.
- Using a color code to show the distribution of information in the signals in both the time domain and frequency domain simultaneously.

These diagrams were produced by translating the statements and logic from the following two textbooks into simple graphics:

Modern Electronic Communication, 6th edition,

Electronic Communication Techniques, 4th edition,

Graphing calculators were used to plot equations, and some of the particularly difficult steps were checked by simulation using Multisim or by TIMS (Telecommunications Instructional Modeling Systems).

The history of preparing this booklet is a long one. Before beginning the arduous work of producing these diagrams, we inspected about 70 standard textbooks on electrical communications to determine whether we could save ourselves a lot of effort by simply using their diagrams; but none of those books contained the above simultaneous diagrams. Some of the basic ideas underlying these diagrams were presented by us in 2001 at a conference of FIE (Frontiers In Education) in Reno, Nevada. Completion of this booklet took about three more years of devoted labor, research, and collaboration.

During the preparation of this booklet, many others at the New York City College of Technology (NYCCT) aided us. Helpful technical suggestions were offered by several of our colleagues:

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- Students: M. B. Suranga Perera, Nikolay Ostrovskiy and Johnny Lam. They produced the professional graphics in these vector art diagrams and created the pages.

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- Former Dean Phyllis Sperling of the School of Technology & Design
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- Federal Work Study Program administered by the Department of Financial Aid at NYCCT.
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Your comments will be used to produce an improved second edition of this booklet. We, the authors, would greatly appreciate being informed of any mistakes or of other comments about this booklet by emailing me: bookletauthor@hotmail.com
INTRODUCTION

To help the reader use this set of diagrams of AM, PM, and FM efficiently, two sets of comments have been added to the diagrams to elucidate them. The first set of comments applies generally to all the diagrams and is included in this introduction. The second set of comments applies specifically to individual diagrams, and each of these comments is inserted in the main text adjacent to the diagram that it explains.

GENERAL COMMENTS

The main objective of these diagrams is to help students understand the operation of transmitters and receivers of various types by showing how the signal changes as it propagates through each stage in a series of cascaded stages, whose electrical operating characteristics are also usually shown in the diagrams. For simplicity the information signal is assumed to be a sinusoid. The signal itself is shown in two adjacent forms:

• in time domain, i.e., how the signal changes in time as it would be observed on an oscilloscope inserted at a particular point in the system

• in frequency domain, i.e., how the signal changes in sinusoidal composition as it would be observed on a spectrum analyzer inserted into the system at the same point as the above oscilloscope. [The diagrams on the FM receiver and the PM receiver violate this rule slightly by showing noise separately.]

Being able to relate these two views of the signal is a major lesson in communications, since beginners usually think only in the time domain; but experts in communications usually think in the more abstract frequency domain. In addition, the mathematical equations for important signals in the time domain have also been inserted to help the student correlate this information with the two graphic forms of the signal.

The general structure of each diagram is as follows. In the left-most column, the various cascaded stages are arranged vertically from top to bottom. Arrows represent the signal flow between the stages. To the right of each arrow and at the same level are the two graphic representations of the signal itself, i.e., first in the time domain and then in the frequency domain. Thus, the three columns of the diagram are arranged from left to right from most concrete to most abstract. In addition, the operating characteristics of some devices, e.g., amplifiers and filters, are also shown. These characteristics are shown in the domain where their operation is most easily represented. For example, the operation of filters is most easily described in the frequency domain; while the operation of a limiter in an FM receiver is most easily described in the time domain.

A color code has been used to draw the various signals in these diagrams mainly to help students trace the flow of information, which is vital to understanding the operation of a communications system. Of course, the real signals or waves are invisible, i.e., colorless, to our eyes; but the colors arbitrarily assigned to the signals in these diagrams show their content of information.

• Blue signals in the time domain or in the frequency domain indicate the pure information signal.

• Red signals indicate the pure carrier wave.

• Purple signals show that the information signal and the carrier wave have been mixed, just as blue and red colors mix to form the color purple.

• Green indicates the operating characteristic in graphs of various devices, like amplifiers and filters.

• Black signals indicate noise.

A somewhat different color code has been used for the arrows showing signal propagation in the left-most column. As above, red arrows mean the carrier wave; and blue arrows mean the information signal. However, the mixed state of carrier plus information is indicated by the split arrow, half being red and half being blue.

In symbols and equations used these diagrams, the red carrier wave is symbolized by “c”; and the blue information signal is symbolized by “m” (not “l” as is used by many texts) since “m” stands for the modulating information. The red arrows mean the carrier wave; and blue arrows mean the information signal. However, the mixed state of carrier plus information is indicated by the split arrow, half being red and half being blue.

The scale of the vertical voltage axis in the time domain differs from voltage scale in the frequency domain because otherwise the size of the bars in the frequency domain would have been too small to have been read easily. To remind the student that these scales are different, an arrow has been drawn and labeled as “amplitude” in the earliest sinusoid in the time domain in each diagram. [“Amplitude” in all these drawings means the amplitude of a sinusoid, not of any other function] This arrow then reminds the reader of how big the amplitude in the frequency domain really is in the time domain.

In general, the wave forms and operating characteristics shown in these diagrams are mere “cartoons,” or idealizations, of reality, not exact pictures. This approximation is appropriate because exact representations would be difficult to understand. For example, in the case of FM as seen in the frequency domain, if the various sidebands were drawn to scale, the sidebands could not easily be distinguished from the carrier in the size of diagrams drawn here.

Finally, the amount of detail shown varies from diagram to diagram. For example, some diagrams show the operating characteristics of ideal amplifiers; others do not. In each case, our aim was to show as much detail as possible without cluttering the diagram.

(continued on page 7)
OPERATION OF ADDER-ANTENNA TRANSMITTER

This diagram shows a transmitter that does not work to emphasize the reason that real transmitters do work. That is, this transmitter leaves the information, which is shown in blue, at low frequencies so that it cannot be radiated; the radiating antenna only broadcasts high frequencies. This implies that only the high-frequency carrier wave is broadcast, which is useless. The aim of a communications system is to broadcast information, not to broadcast the pure carrier wave!
OPERATION OF AM TRANSMITTER IN GENERAL
This transmitter works, while the previous one fails, because the AM modulator raises the information, shown in blue, to high frequencies so that it can be broadcast along with the carrier by the high-pass antenna. The AM modulator automatically raises the frequency of the information when encoding information by changing the amplitude of the carrier sinusoid.

AMPLIFIER
AM MODULATOR
ANTENNA

Low Frequency Information
High Frequency Carrier

Voltage (Volts)

Low Frequency Information
High Frequency Carrier

Time (Sec.)

Combined Signal

Voltage (Volts)

Combined Signal

Time (Sec.)

Amplifier gain = constant K>1.

Amplifier gain = constant K>1.

Antenna Gain

Amplifier Gain

Gain of Filter

Filter selects carrier and sidebands.

Amplifier Gain

Amplifier gain = constant K>1.

Amplifier gain = constant K>1.

Antenna passes only high frequencies.

Antenna passes only high frequencies.

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OPERATION OF AM TRANSMITTER SHOWING AM MODULATOR IN DETAIL
This diagram differs from the previous one only in that it shows the details of the AM modulator. The operation of the modulator consists of two stages. First, the information signal and carrier are passed through a nonlinear device, e.g., a transistor or diode, to generate the required upper and lower sidebands along with unnecessary sinusoids of many other frequencies. [The diagram mentions an "ideal" nonlinear device; "ideal" means that most of the unnecessary harmonics have been omitted for clarity.] Second, a high-frequency bandpass filter removes the unnecessary sinusoids and passes only those in the required AM-modulated carrier.

AMPLIFIER
AM MODULATOR
BAND-PASS FILTER
ANTENNA

Low Frequency Information (blue)
High Frequency Carrier (red)

Voltage (Volts)

Low Frequency Information (blue)
High Frequency Carrier (red)

Time (Sec.)

Combined Signal

Voltage (Volts)

Combined Signal

Time (Sec.)

Gain of Filter

Filter selects carrier and sidebands.

Amplifier Gain

Antenna Gain

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OPERATION OF TRF AM RECEIVER

The main point of interest here is the structure of the AM detector. The basic structure of the AM detector and of the AM modulator are the same: a nonlinear device followed by a bandpass filter. In the detector, the nonlinear device reproduces the original signal sinusoid from the AM-modulated carrier and also produces many unnecessary sinusoids of other frequencies; the filter removes these unnecessary sinusoids and passes the original information signal. The main difference between the AM modulator and the AM detector is the frequency band passed by the filter: the modulator passes a band at high radio frequencies; the detector passes a band at low audio frequencies.

OPERATION OF SUPERHETERODYNE AM RECEIVER

The structure of this receiver and that of the TRF receiver are very similar. The main difference is the frequency range in which most of the signal amplification is done. The TRF receiver amplifies the signal at the same high radio frequencies at which it is received initially by the antenna. Unfortunately, amplification at these high frequencies is inefficient; i.e., the amplifier gains are low. To correct this error, the superheterodyne receiver does most of its signal amplification at a lower "intermediate frequency" band for greater efficiency. Since this intermediate frequency band is the fixed passband of the filter in the IF amplifier, each incoming signal must be lowered to this fixed intermediate frequency band by using a frequency converter, which consists of a mixer (which is a nonlinear device) connected to an oscillator of variable frequency. This is called the "local oscillator." By changing the oscillator frequency appropriately, any station's signal can be lowered to the given intermediate frequency range for efficient amplification.
OPERATION OF PM TRANSMITTER
Both the FM transmitter and PM transmitter have similar structures. The main difference between them is the kind of modulator used. FM modulators encode information by changing the frequency of the carrier wave. PM modulators encode information by changing the phase of the carrier wave.

Amplifier gain = constant $K > 1$.

Preemphasis amplifies high frequencies to overcome high-frequency noise in the FM receiver.

Antenna passes only high frequencies.

Amplitude (Volts)

Time (Sec.)

Frequency (Hz)

Amplitude (Volts)

Time (Sec.)

Frequency (Hz)

Amplitude (Volts)

Time (Sec.)

Frequency (Hz)

Amplitude (Volts)

Time (Sec.)

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Time (Sec.)

Frequency (Hz)
**OPERATION OF FM TRANSMITTER WITH INDIRECT MODULATION**

There are two general types of FM modulators. In the first type, i.e., those with indirect modulation, the carrier wave is produced by a very stable oscillator located outside the modulator itself, as is also done in PM modulation. The indirect FM modulator is just a PM modulator preceded by a special stage that integrates the information signal; this integration is carried out by passing the signal through an amplifier whose gain is inversely proportional to frequency.

![Diagram of FM transmitter with indirect modulation](image)

**OPERATION OF FM TRANSMITTER WITH DIRECT MODULATION**

In the second type of FM modulation, i.e., direct modulation, the oscillator producing the carrier wave, is actually incorporated into the FM modulator itself. Otherwise, FM transmitters with direct modulation and those with indirect modulation are essentially the same.

![Diagram of FM transmitter with direct modulation](image)
OPERATION OF FM RECEIVER

The FM receiver is very similar to the superheterodyne AM receiver. The main difference is that the FM receiver uses an FM demodulator; while the superheterodyne AM receiver uses an AM demodulator.

In addition, the FM receiver has two stages for noise control that the AM receiver lacks. First, just ahead of the demodulator, there is a limiter to clip off and thereby remove external noise. [This cannot be done in AM because clipping the noise would also remove the information, that is encoded in the amplitude of the carrier wave.] Second, after demodulation in the FM receiver, there is a deemphasis stage, that is involved in combating internal noise. The deemphasis stage corrects the earlier distortion of the signal in the preemphasis stage of the FM transmitter, where high-frequency sinusoids are amplified more than low-frequency ones.

In the FM transmitter, the purpose of distorting the signal is to facilitate the receiver’s detecting the signal’s high frequencies in the presence of high-frequency noise. This noise is generated inside the FM demodulator in the receiver. Basically the deemphasis in the receiver is also a nonuniform amplifier which corrects the initial distortion in the transmitter by emphasizing the low frequencies over the high frequencies (i.e., deemphasizes the high frequencies) which were preferentially amplified (i.e., emphasized) by the preemphasis stage in the FM transmitter.

In contrast to the AM receivers, the diagram of the FM receiver also shows a noise signal although noise is really present in both types of receivers. However, noise is only shown in the FM case because only FM receivers have special stages to combat noise, i.e., the limiter for external noise and the deemphasis stage for internal noise. AM receivers have no special stages to combat noise.

To simplify the description of the operation of the FM receiver in the presence of noise, we consider that the external noise is white noise (i.e., noise consisting of sinusoids of all frequencies and all with the same amplitude) generated by an impulse and that this noise can be treated separately from the modulated FM signal. This latter simplification is justifiable when all of the modulated FM signal passes through a filter.

Note that in contrast to all preceding diagrams, in the diagram of this FM receiver and of the following FM receiver, the graphs of the time domain and of the frequency domain are not exactly the same as the output of an actual oscilloscope or of an actual system analyzer. This is because only in these diagrams noise is not combined with the FM or PM signals to produce the total signal that the real instruments display in different forms.
OPERATION OF PM RECEIVER

The PM receiver and the FM receiver are basically the same except that the PM receiver has no deemphasis stage, since there is no need for one. This is because in the PM transmitter there is no preemphasis stage to initially distort the signal. Therefore, there is no need in the PM receiver for a deemphasis stage to correct this non-existent distortion.

CONCLUSION

It is hopeful that the above comments will help the reader to better understand and use the associated diagrams. These relevant graphics can in a simple way give a student a global view of the complex subject of radio transmitters and receivers.

The communications circuits that are diagrammed here can also be simulated on a computer, e.g., by using Multisim. However, our diagrams have the following advantages over simulation alone:

1) global view: The form of the signal can be seen simultaneously at all stages in the cascade instead of only at a few stages at time as in the simulations. Thus, the overall operation of the system is much easier to grasp in these diagrams than by simulation alone.

2) operational characteristics: The diagrams show the operational characteristic of the filters, amplifiers, and other parts of the circuit. Simulation does not.

3) distribution of information: By using a color code, these diagrams show where in the signal the information lies; simulation does not. Knowing the location of the information is critical to understanding the operation of the communication system.

Hence, these diagrams support and enhance the use of simulation by providing a more comprehensive view, operational characteristics of devices, and color coding to locate the information.
The purpose of these diagrams is to graphically explain the overall operation of AM, PM, and FM communications systems using very little mathematics.