Chapter 1 Notes

Electronic Communications Systems, 5th edition, W. Tomasi
Introduction to Electronic Communications

Signals for Conveying Information

An **analog signal** varies continuously with time, with no breaks or discontinuities. Examples of an analog signal:

Electrical signal (voltage vs. time) from a microphone
Line Out of an MP3 Player
Electrical signal (voltage vs. time) from a phototransistor

A **digital signal** maintains a constant value for a fixed period of time and then changes to a different level. Examples of a digital signal:

Data line on a PC motherboard from flash memory to central processing unit (CPU)
Data out of an Analog-to-Digital Converter (ADC)
Data line inside a cell phone from the cell phone camera's charged-coupled device (CCD) to the digital signal processor (DSP).

Sine wave:

$$s(t) = A\sin(2\pi f t + \phi)$$

where A is the amplitude,
f is the frequency of the sine wave in Hz,
t is the time in second, and
ϕ is the phase angle in radians.

Electromagnetic (EM) waves are used to send information wirelessly. EM waves vary in space and time. The expression for the electric field of an EM wave in free space is:

$$E(x,t) = A\sin\left(2\pi f t + \frac{2\pi x}{\lambda} + \phi\right)$$

where A is the amplitude,
f is the frequency of the EM wave in Hz,
x is the distance of the EM wave in meters from the source,
the x axis is the direction of propagation,
λ is the wavelength in meters per cycle, and
ϕ is the phase angle in radians,
E is the electric field intensity in volts per meter.

The electromagnetic wave travels through space as a sinusoidal waveform of voltage and magnetism. You cannot see the electromagnetic wave with the human eye, but it is there. One needs instruments such as antennas and oscilloscopes to detect the electromagnetic wave. The length of one period of an electromagnetic wave in space is called the **wavelength** and is measured in meters per cycle. Mechanical systems also experience the wavelength of mechanical vibrations. For instance, think about a jump rope. Suppose you tie one end to a fixed object and pull the rope tight. Then shake the rope while pulling it tight. You will generate waves that travel down the rope. The waves are sinusoidal. If you took a photograph of the rope while it is vibrating, you could measure the length of these waves. You will note that you can change the wavelength by shaking the rope faster.

The wavelength can be calculated using:

$$\lambda = \frac{v}{f}$$

where λ is the wavelength of the transmitted wave in meters per cycle
f is the frequency of the transmitted wave in Hz (or cycles per second)
v is the speed of the wave in meters/sec

Example 1.
Suppose you want to generate waves that are 1 meter long and move 10 miles per hour down a jump rope. Calculate the frequency at one must vibrate the rope.

In free space, electromagnetic waves have a wave velocity equal to the speed of light which is 3×10^8 meters/sec . In this case, the wavelength can be calculated using:

$$\lambda = \frac{c}{f}$$

where λ is the wavelength of the transmitted wave in meters per cycle
f is the frequency of the transmitted wave in Hz (or cycles per second)
c is the speed of (3×10^8 meters/sec) in free space

Example 2.
A cellular telephone receives signals in the 900 MHz frequency band. Compute the wavelength of the received signal.

Principles of wireless communication
The goal of wireless communication systems is to send signals over large distances with minimal distortion, low power and low cost. Effects such as atmospheric noise and interference from other communication systems tend to distort the intended signal. So one goal of a communication system is to suppress atmospheric noise and interference. Low power is desirable because it reduces health hazards. There are definite health hazards concerning the

exposure to high power electromagnetic waves. One can be blinded by high power electromagnetic waves whose wavelength is close to the diameter of the eye. The human body can be badly burned by exposure to high power electromagnetic waves whose frequency is close to the resonant frequency of water. Hence, there is a great need to reduce power while maintaining quality of the received signal in wireless systems. Low cost is especially important for the users of communication systems.

We will start our discussion of the principles of wireless communication systems by looking at antennas. All wireless systems make use of antennas for transmission and reception. Antennas send and receive electromagnetic waves. There are two basic types of antennas: **linear** antennas and **aperture** antennas. Linear antennas are constructed using straight wires. Aperture antennas are constructed with cables connect to horn-like openings. The antenna in a cell phone is a type of linear antenna called a **monopole**. Most car antennas are also monopoles. The FM antenna used for a stereo set is a type of linear antenna called a **dipole**. An outdoor antenna used for TV reception is a linear antenna called a **yagi** antenna. The antenna used for satellite reception is an aperture antenna called a **parabolic reflector**.

Antennas will work most efficiently within a given frequency range, that depends upon the size of the antenna. Monopole antennas, for example, work most efficiently when the wavelength is 4 times the length of the antenna. Dipole antennas work most efficiently when the wavelength is 2 times the length of the antenna. Parabolic reflectors work efficiently when the diameter of the antenna is larger than 10 wavelength. Cost of the parabolic reflector usually prohibits going over 100 wavelengths.

Example 3.
A monopole antenna is designed to operate at 100 MHz. What should the antenna length be?

The types of signals that we often would like to send are voice and music signals. The frequency range of voice is about 10 to 12000 Hz. Most of the energy of the voice signal is in the 50 to 200 Hz range. The frequency range of music is from 20 to 20000 Hz. If we were to design an antenna to send these signals directly via wireless means, the resulting antenna length would be huge. Example 4 demonstrates this phenomenon.

Example 4.
Suppose we wanted to wirelessly send a voice signal that is in the 100 to 200 Hz range by direct connection to a monopole antenna. What should the antenna length be? For simplicity use a frequency of 150 Hz.

As seen Example 4, we would need an antenna that is over 300 miles long to send a voice signal wirelessly through a monopole antenna! That is absurdly long.

In order to use a smaller antenna, we need a higher frequency. To explain this look at the equation for the wavelength of an electromagnetic wave:

$$\lambda = \frac{c}{f}, \qquad \text{and re-arrange it as} \qquad \lambda f = c$$

Since the speed of light (*c*) is constant, if we increase *f*, then we would have to decrease the wavelength (λ) to make the equation balance. Since antenna size is proportional to wavelength, then the antenna size would go down also. That is what we want, a smaller antenna — don't want antennas 300 miles long.

But how do we increase the frequency of a given signal to allow us to use a smaller antenna? This problem is overcome with the use of modulation and demodulation. Modulation is the process of translating a signal from a low frequency range to a higher frequency range. Demodulation is the process of translating a signal from a high frequency range to a low frequency range.

To explain how modulation and demodulation works, let's return to the voice example. Recall in example 3 that a 100 MHz signal has a very reasonable wavelength of 3 meters, resulting in a monopole antenna length of 0.75 meters. That is a good size of antenna to work with – about 2 feet long—much better than 300 miles, anyway. So we take the 100 to 200 Hz voice signal, put it through a 100 MHz modulator. The modulator adds 100 MHz to the range of the voice signal. This results in a frequency range of 100 MHz + 100 Hz to 100 MHz + 200 Hz. In other words, the modulator output has a frequency range of 100000100 to 100000200 Hz. Send this signal through a 0.75 meter antenna. Then many miles away at the receiver side, we would have a similar 0.75 meter antenna to receive the signal. Then we would send the signal through a 100 MHz demodulator. The demodulator simply subtracts 100 MHz from the incoming signal to retrieve the original:

100000100 – 100000000 = 100 Hz
100000200 – 100000000 = 200 Hz

So the range of the demodulated signal is 100 to 200 Hz, the same as the original voice signal. The demodulated signal is then sent to an audio speaker, allowing us to hear the person's voice.

So that is a quick and simplified summary of how wireless communications works. Here is a summary of the main steps:

1) Send the desired signal through a **modulator** to boost the frequency of the signal to a higher range. The output of the modulator is called the **modulated signal**.
2) Send the modulated signal through an antenna designed for the higher frequency range. The antenna transmits an electromagnetic wave through the atmosphere.
3) Receive the electromagnetic wave with a similar type and size antenna.
4) Send the received signal through a **demodulator** to down-convert the frequency range back to the range of the original signal.

The electromagnetic spectrum

As shown in Figure 1, the electromagnetic spectrum for Telecommunications has five bands:

Power and telephone, audio equipment, 20 – 20000 Hz
Radio frequencies, 10 kHz – 1 GHz
Microwave frequencies, 1 – 300 GHz
Infrared frequencies, 300 GHz – 200 THz
Visible light frequencies, 200 – 1000 THz

In the US, most use of the electromagnetic spectrum is allocated by law, by the Federal Communication Commission (FCC). Of these five bands, **Radio**, **Microwave**, and **Infrared** frequencies are used for wireless applications.

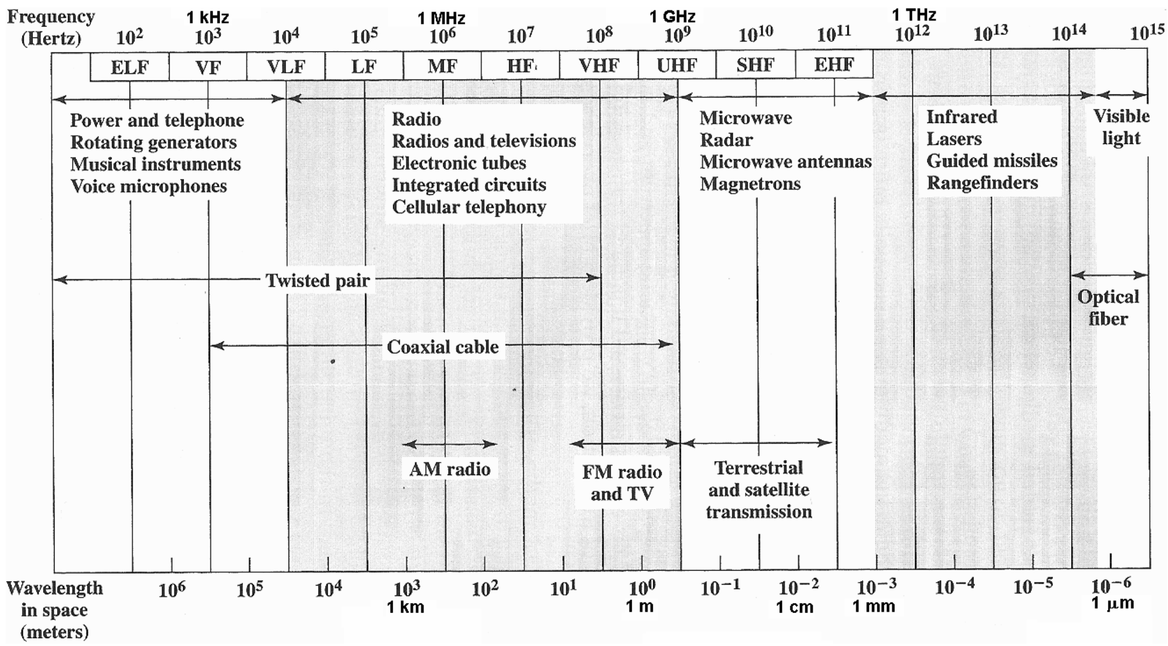

Figure 1. Electromagnetic Spectrum. From William Stallings, *Communications and Networks*, Second Edition, Prentice Hall, 2005, p. 32.

Many telecommunications applications make use of standard three letter abbreviations to identify the frequency band. These bands are identified in Table 1. In this table, both frequency and wavelength are provided. Metric prefixes used to express units of frequency and wavelength are provided in Table 2.

Table 1. Standard Telecommunication Frequency Bands

ITU Band	**Frequency Band**		**Frequency Range**	**Wavelength Range**
2	**ELF**	Extra Low Frequency	30 – 300 Hz	1000 – 10000 km
3	**VF**	Voice Frequency	300 – 3000 Hz	100 – 1000 km
4	**VLF**	Very Low Frequency	3 – 30 kHz	10 – 100 km
5	**LF**	Low Frequency	30 – 300 kHz	1 – 10 km
6	**MF**	Medium Frequency	300 kHz – 3 MHz	0.1 – 1 km
7	**HF**	High Frequency	3 – 30 MHz	10 – 100 meters
8	**VHF**	Very High Frequency	30 – 300 MHz	1 – 10 meters
9	**UHF**	Ultra High Frequency	300 MHz – 3 GHz	0.1 – 1 meter
10	**SHF**	Super High Frequency	3 – 30 GHz	1 – 10 cm
11	**EHF**	Extremely High Frequency	30 – 300 GHz	1 – 10 mm
12	Infrared		300 GHz – 3 THz	0.1 – 1 mm
13	Infrared		3 – 30 THz	10 – 100 μm
14	Infrared		30 – 300 THz	1 – 10 μm
15	Visible Light		300 THz – 3 PHz	0.1 – 1 μm
16	Ultraviolet Light		3 – 30 PHz	10 – 100 nm
17	X Rays		30 – 300 PHz	1 – 10 nm
18	Gamma Rays		300 PHz – 3 EHz	0.1 – 1 nm
19	Cosmic Rays		3 – 30 EHz	10 – 100 pm

Table 2. Standard Metric Prefixes Used in Telecommunications

Multiplier	**Metric Prefix**	**Designation**
10^{-15}	f	femto
10^{-12}	p	pico
10^{-9}	n	nano
10^{-6}	µ	micro
10^{-3}	m	milli
10^{3}	k	kilo
10^{6}	M	mega
10^{9}	G	giga
10^{12}	T	tera
10^{15}	P	peta
10^{18}	E	exa

Terrestrial Microwave

Terrestrial microwave requires line-of-sight from transmitting antenna to receiving antenna. A 1 meter parabolic dish is typically used for both transmission and reception. The typical frequency range is 2 – 40 GHz.

22 Ghz is used for point-to-point communications between buildings as part of a local area network.

Satellite Microwave

The satellite is a relay from a transmitting earth station to a receiving earth station. Satellites have transponders which receive uplink signals, convert the signals to a different carrier and transmit the downlink at a different carrier frequency,

Applications of satellite microwave:

- Television
- Telephone
- Private business lease of satellite channels
- Government Agencies

C-Band satellite communications which is 6 GHz on the uplink and 4 GHz on the downlink is commonly used for long-distance communications.

K-Band satellite communications which is 14 GHz on the uplink and 12 GHz on the downlink is commonly used for direct satellite TV to homes.

There is use of 40 and 60 GHz for point-to-point communications between satellites. In space, there is no absorption due to water vapor, so higher frequencies can be used for satellite-to-satellite communication links.

Frequency Range: Earth-to-satellite and satellite-to-earth microwave is most suitable for the 1 to 10 GHz range. Below 1 GHz, there is excessive noise from terrestrial sources which interfere with the very weak signals that are received from the satellite by the receiving earth station. Above 10 GHz, earth-to-satellite and satellite-to-earth links are severely attenuated by water vapor, rain, and cloud cover.

Satellite and earth station antennas are highly directional.

<u>Broadcast radio</u>

Freq. Range: 30 MHz – 1 GHz
Antennas: Omnidirectional (donut-shaped antenna pattern), horizontal or vertical dipole.

<u>Infrared</u>

Freq. Range: 300 GHz – 200 THz
Antennas: directional
Path: Point-to-point, or by reflection

Infrared does not penetrate walls. So home use of infrared requires no Federal Communication Commission (FCC) allocation, and no license is required.

Section 1-2 Power Measurements (dB, dBm, dBW)

Consider an audio amplifier with Power in and Power out:

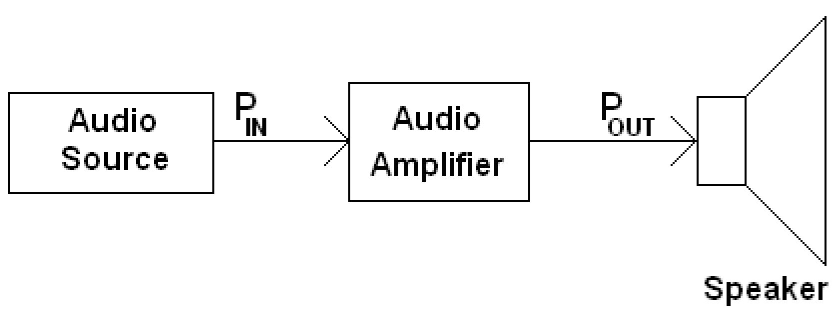

Figure 2. Measurement of Power Gain in an Audio Amplifier

The power gain of the amplifier is:

$$A_P = \frac{P_{out}}{P_{in}}$$

where P_{in} is the power delivered to the amplifier input terminal in watts, and
P_{out} is the power delivered from the amplifier input terminal in watts.

Since the power gain is a division of power in watts, the result is that power gain is a unitless quantity. A power gain of 20 means that the output power is 20 times the input power. One cannot determine the output power from the power gain alone. The power gain only let's one know what the ratio between output and input power is.

The gain of the amplifier in decibels is:

$$A_{P(dB)} = 10\log_{10} A_P = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Values of gain in decibels are shown in Table 3.

Table 3. Values of decibels given various values of power gain

Power gain, $\boldsymbol{A_P}$	Power gain in decibels, $A_{P(dB)}$	Relation between input and output power
10^{-5}	-50	$P_{out} = 10^{-5} \times P_{in}$
10^{-4}	-40	$P_{out} = 10^{-4} \times P_{in}$
10^{-3}	-30	$P_{out} = 10^{-3} \times P_{in}$
10^{-2}	-20	$P_{out} = 10^{-2} \times P_{in}$
10^{-1}	-10	$P_{out} = 0.1\ P_{in}$
1	0	$P_{out} = P_{in}$
10	10	$P_{out} = 10P_{in}$
100	20	$P_{out} = 100P_{in}$
1000	30	$P_{out} = 1000\ P_{in}$
10^4	40	$P_{out} = 10^4 \times P_{in}$
10^5	50	$P_{out} = 10^5 \times P_{in}$

Example 5.
An MP3 player delivers 10 µW of an audio music source to an audio amplifier. The amplifier delivers 100 watts of the same music to a speaker. Compute the power gain of the amplifier as a unitless ratio and in dB.

Consider a transmission line with Power in and Power out:

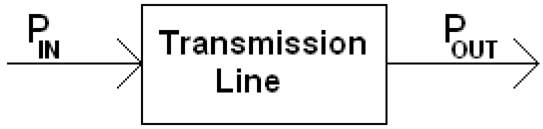

Figure 3. Transmission Line

The transmission line will have some power loss, which is defined as:

Power Loss in watts = $P_{OUT} - P_{IN}$

Question: Since there is power loss in a transmission line, where does the lost power go?

The power loss factor of the transmission line is:

$$L = \frac{P_{in}}{P_{out}}$$

In decibels, the power loss factor is:

$$L_{dB} = 10\log_{10} L = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

Since $\frac{P_{in}}{P_{out}}$ can be written as $\frac{P_{in}}{P_{out}} = \left(\frac{P_{out}}{P_{in}}\right)^{-1}$ then we can write loss in dB as:

$$L_{dB} = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

$$= 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)^{-1} = -10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) = -A_{P(dB)}$$

So we have shown that: ***Power Loss Factor in dB = - Power Gain in dB***.

Example 6.
A transmission line is 1 mile long. The power entering the transmission line is 12 mW. The power leaving the transmission line is 4 mW. Compute the transmission line power loss factor in dB.

Net Gain

Net Gain of a network may be computed by adding all the power gains (in dB) of each element and subtracting all the power losses (in dB). Using this fact can allow one to compute overall power out and individual powers within the network, as illustrated in the example 7.

Example 7.
A communication network is shown in Figure 4. The first amplifier has a gain of 20 dB, the second amplifier has a gain of 10 dB. The transmission line has a loss of 23 dB. Suppose the input power is 3 mW.
(a) Determine the output power (P_{out}).
(b) Determine the power out of the first amplifier (P_{out1}).
(c) Determine the power out of the transmission line (P_{out2}).

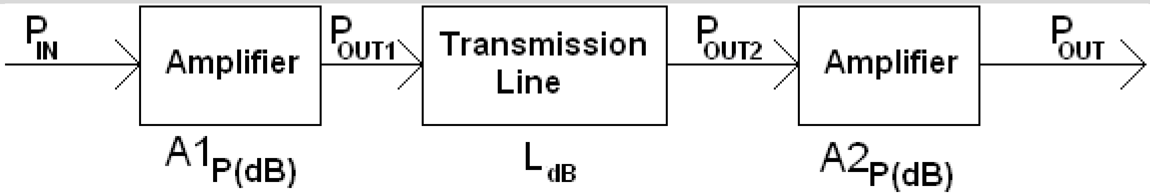

Figure 4. Communication network

<u>Units of power in decibels</u>

Since power gains and losses in dB can easily be added and subtracted, a system of placing power in dB was developed to avoid the antilog scheme of the previous examples. **dBW** is a unit for expressing power in watts as decibels above one watt:

$$Power_{dBW} = 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{watt}}\right)$$

Similarly, we can express power in decibels relative to 1 mW. This unit is **dBm** and is computed as:

$$Power_{dBm} = 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{mW}}\right)$$

The conversion between dBm and dBW is derived below:

$$\begin{aligned} Power_{dBm} &= 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{mW}}\right) \\ &= 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{mW}}\right)\left(\frac{1000\,\text{mW}}{1\,\text{W}}\right) \end{aligned}$$

Cancel mW to get:

$$
\begin{aligned}
Power_{dBm} &= 10\log_{10}\left(\frac{(1000)\text{Power in watts}}{1\,\text{W}}\right)\\
&= 10\log_{10}\left[\left(\frac{\text{Power in watts}}{1\,\text{W}}\right)\left(10^3\right)\right]\\
&= 10\left[\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{W}}\right)+\log_{10}\left(10^3\right)\right]\\
&= 10\left[\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{W}}\right)+3\right]\\
&= 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{W}}\right)+30
\end{aligned}
$$

Substitute $Power_{dBW} = 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{watt}}\right)$ above to get:

$$
\begin{aligned}
Power_{dBm} &= 10\log_{10}\left(\frac{\text{Power in watts}}{1\,\text{W}}\right)+30\\
&= Power_{dBW} + 30
\end{aligned}
$$

So dBW is converted to dBm by adding 30. Why is this? Consider an amplifier with a gain of 1000. If the input power is 1 mW, then the output power is 1 W. A gain of 1000 corresponds to a gain in dB of 30 dB.

Example 8.
Compute the power of 4 watts in dBW and in dBm.

To find the output power of a network, one can add the net gain to the input power in dBW to obtain the output power in dBW:

$$Power\ out_{dBW} = \text{Net Power Gain in dB} + Power\ in_{dBW}$$

Similarly, one can add the net gain to the input power in dBm to obtain the output power in dBm:

$$Power\ out_{dBm} = \text{Net Power Gain in dB} + Power\ in_{dBm}$$

An example below illustrates the use of this method.

Example 9.
A communication network is shown in Figure 4. Suppose the first amplifier has a gain of 8 dB, the second amplifier has a gain of 16 dB. The transmission line has a loss of 12 dB. Suppose the input power is 5 dBm. Determine the output power (P_{out}) in dBm and in dBW.

Spectrum Analyzer Measurements

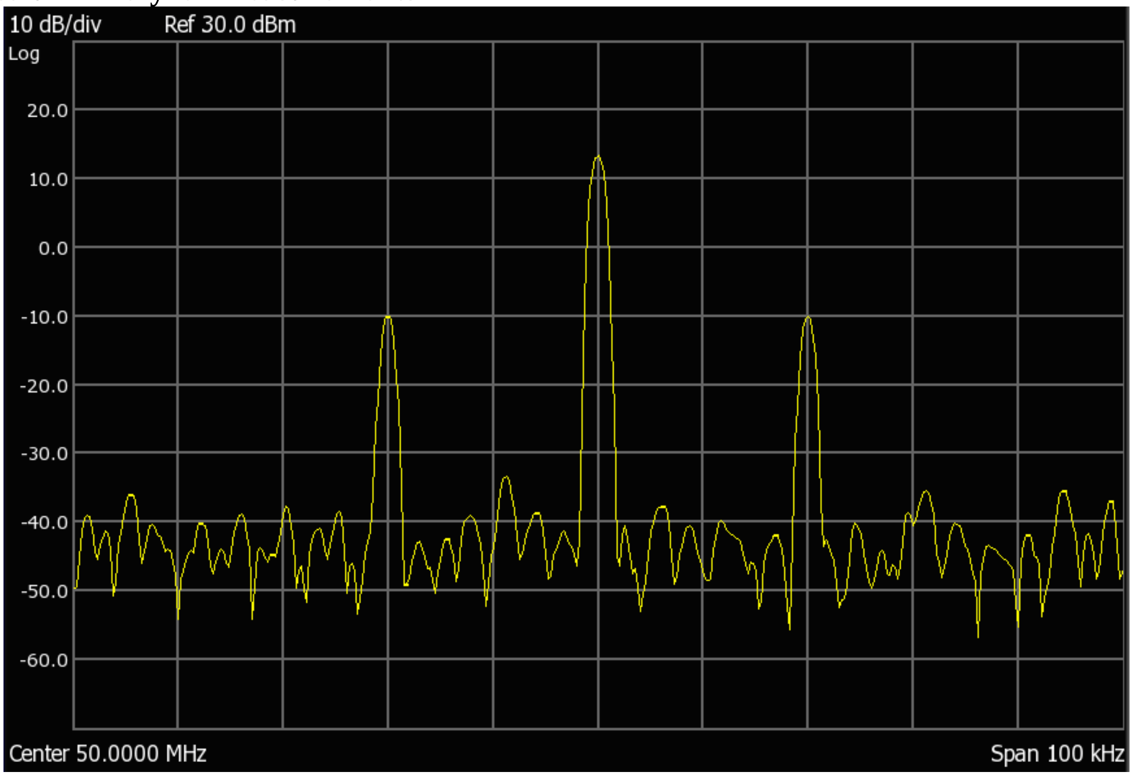

Figure 5. Sample Spectrum Analyzer display

Note the following frequency information concerning the waveform in Figure 5:

Center frequency = 50 MHz
Frequency span = 100 kHz

There are 10 divisions on the horizontal scale, so the frequency per division is

frequency per division = Frequency span / 10 = 100 kHz / 10 = 10 kHz.

Note that there are three main frequencies displayed. We can calculate each as follows:

f_1 = center frequency – 2 divisions = 50 MHz – (2)(10 kHz) = 50 MHz – 20 kHz
= 50 – 0.02 MHz = **49.98 MHz**
f_2 = center frequency = **50 MHz**
f_3 = center frequency + 2 divisions = 50 MHz + (2)(10 kHz)
= 50 MHz + 20 kHz
= 50 + 0.02 MHz = **50.02 MHz**

Note the following power information concerning the waveform in Figure 5:
The power of frequencies f_1 and f_3 are both **-10 dBm.**
The power of frequency f_2 is about **13 dBm.**

Noise Floor. The noise floor is the level at which no intelligible information can be obtained. In the screen shot in Figure 5, the noise floor is about **– 40 dBm.**